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THEORETICAL INVESTIGATION OF VARIABLE PERIODICITY (GRADED) MULTILAYERS FOR HARD X-RAY APPLICATIONS

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by

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SUMMARY OF RESULTS

The objective of this research was to investigate the possibility of increasing the useful bandwidth of multilayer mirrors. Mirrors "constructed" with non-periodically spaced reflecting surfaces were considered. These structures included depth-graded and laterally-graded mirrors as well as those with reflectors located via a log-periodic spacing rule.

No enhancement of bandwidth resulted from simulations of simple versions of any of the three non-periodic mirrors. However, certain depth-graded structures did exhibit reflectances essentially the same as from uniform mirrors. Moreover, it was found that some control was possible regarding the location (with respect to energy) of the maximum reflectance peak.

Effective bandwidth was increased when composite models were simulated. In two of the cases studied, bandwidth was enhanced by a factor of approximately 3. One model consisted of a depth-graded mirror constructed with three separately defined structures, or blocks. Each block consisted of two layer-pairs repeated three times. Then, the entire 18 layer-pair group was repeated several times. Simulation of this 3 block depth-graded configuration yielded three reflectance peaks, one representative of each depth-graded block.

The other configurations resulting in enhanced bandwidth assumed independently constructed mirrors immediately adjacent to each other and sharing the same substrate. Reflectance peaks from each mirror appeared in the response.

Both basic models show greatly enhanced effective bandwidths even though the reflectance curves appear as non-overlapping for these specific models. Additionally, these configurations are realizable. Details are contained in the section, DESIGN SIMULATIONS.

INTRODUCTION

The object of the investigations reported below was to identify parameters and configurations leading to enhanced broadband reflectance of multilayer mirrors. Three non-periodic configurations were studied via simulations using SHADOW, the well known ray-tracing computer program developed at the University of Wisconsin by Professor Franko Cerrina. More specifically, the SHADOW utility program MLAYER, written by J. H. Underwood of the Center for X-ray Optics was utilized in reflectivity calculations. Auxiliary codes were developed at LSU to describe the thicknesses of layer pairs for each mirror configuration, a necessity for this use of MLAYER.

The assumptions inherent with the use of SHADOW are that ray-tracing methods are valid and that the incident x-ray wave "perfectly" intersects the mirror surface (infinitely large mirror assumption). Finally, all incident waves are assumed to be parallel and uniform in spectral intensity.

A journal article[1] published in 1983 compared the calculated responses of idealized flat depth- and laterally-graded multilayers with the corresponding uniform multilayer. These simulations were used to verify the initial use of SHADOW as well as to compare the more practical results of this project. The cited results were for a uniform multilayer with a pair thickness of d = 25.5 Å, a depth-graded mirror with an increase in each d spacing of approximately 0.08 Å (40 layers, centered about 25.5 Å, with d-spacings from 24.13 Å to 27.38 Å), and a laterally graded geometry involving the same minimum and maximum d-spacings as the depth-graded model. In each case, 40 layer pairs were assumed and the grazing angle was fixed at 9.4°. Materials used were carbon and tungsten (W/C) on a silicone substrate. The energy range was centered at 1500 ev.

[1] Ping Lee, *Applied Optics*, **22**, No. 8, April, 1983

After verification of LSU codes using SHADOW by comparison with the cited ("reference") results, parametric studies were performed with similar mirrors. That is, 40 layer pair (W/C on silicone), mirrors were assumed with a grazing angle 9.4°, energy range roughly centered at 1500 ev, etc.

The narrow band reflectance vs energy response (fixed grazing angle) typical of uniform multilayers is shown in Figure 1. This high reflectance characteristic can be obtained at arbitrary (non-zero) grazing angles following the equation below for pseudo-Bragg reflections.

$$\lambda = 2d \sin (o_g) \tag{1}$$

where d = layer pair thickness

o_g = grazing angle

λ = wavelength of incident energy

In this project, three non-periodic multilayer mirror configurations were simulated for comparison with uniform mirrors. They are depth-graded, laterally-graded and mirrors whose reflecting surfaces are located using a log-periodic rule. In the depth-graded mirror geometry, layer pairs parallel to the surface have continuously (linearly) increasing or decreasing thicknesses (see Fig. 2). The laterally-graded geometry consists of layers with thicknesses varying laterally along the surface of the mirror (see Fig. 3). In this study, the lateral direction was defined to be the same as the direction of that component of the incident wave motion parallel to the flat mirror surface.

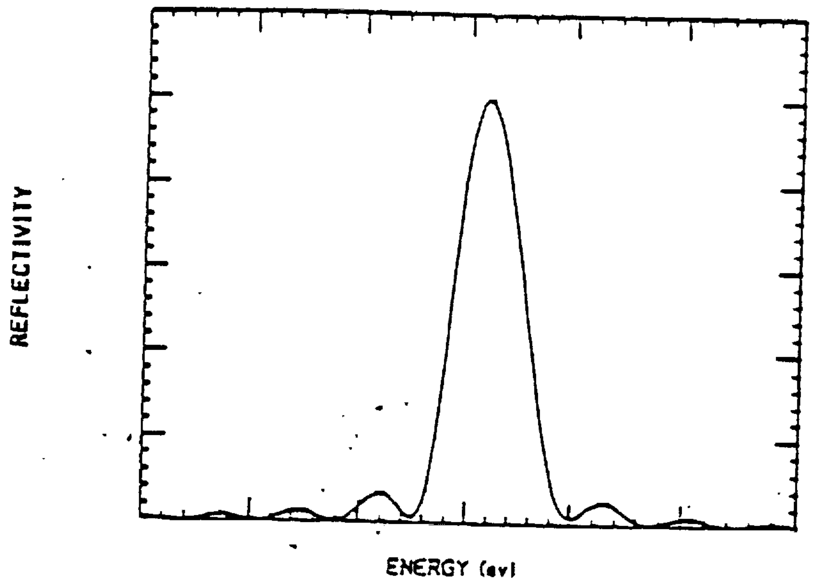


Figure 1. Reflectance vs. Energy for a periodic multilayer simulation.

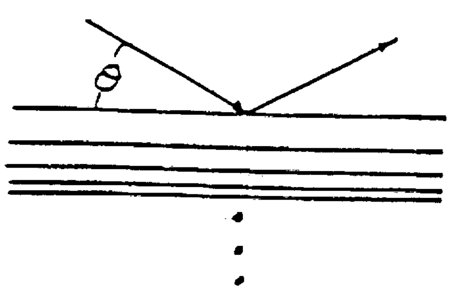


Figure 2. Model of depth-graded multilayers.

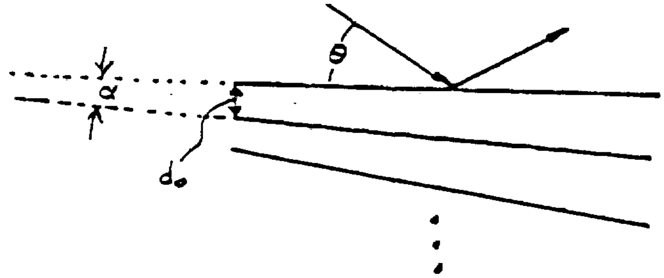


Figure 3. Model of laterally-graded multilayers.

The third mirror geometry simulated is similar to the depth-graded configuration except that the location of reflecting surfaces follows the log-periodic rule,

$$t \equiv D_n/D_{n+1} \qquad \text{or} \qquad t \equiv D_{n+1}/D_n \tag{2a}$$

$$D_n = D_n = D_o t^n \tag{2b}$$

where D_n = depth of the n-th pair (either substrate or surface can be used as the reference plane)

D_o = depth of the reference (initial) pair

t = log-periodic parameter

Figure 4 shows simulations using SHADOW of the depth-graded and uniform mirrors described in Reference 1 as well as of a log-periodic mirror simulation using the same overall range of depths and number of layers as the depth-graded case. Note that the depth-graded and log-periodic response curves are almost identical. The depth-graded and laterally-graded reference cases are totally unrealistic at x-ray energies but do show significant broadening (theoretically) of the reflectance as a function of energy in the limit of total control over mirror layer thickness. Similarly for log-periodic simulations with correspondingly small d-spacings.

In the paragraphs below the results of simulation studies with each of the three non-periodic geometries are presented. In each case the grazing angle, number of layer-pairs (when possible), materials, and energy range used was the same as cited in the reference article. This was done for ease of comparison.

The last sections deal with mirror design using results of the parametric studies. In the design simulations, grazing angle was used as a variable and the energy range considered spanned the 1.78 Å - 1.88 Å wavelength range. Again, carbon/tungsten on a silicon substrate was assumed.

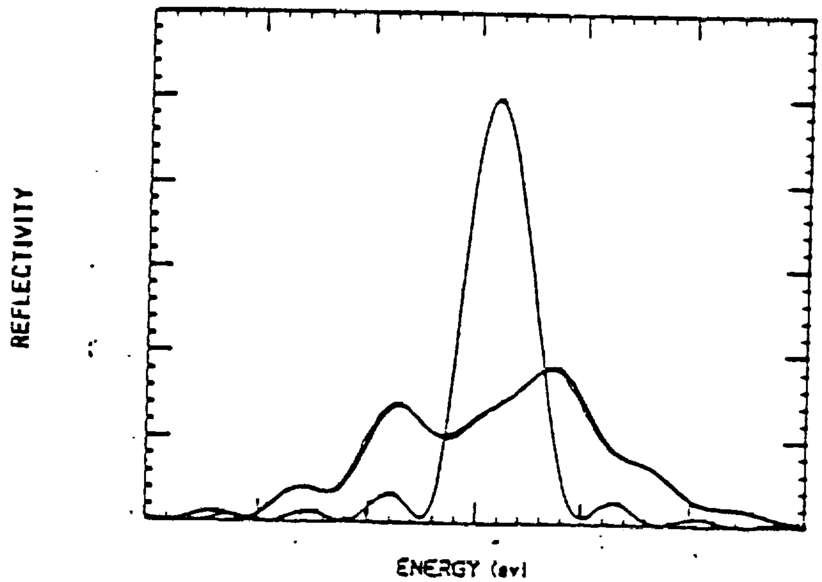


Figure 4. Reflectance for depth-graded and log-periodic multilayer simulations compared with response of periodic multilayer of Fig. 2.

PARAMETRIC STUDIES

Laterally-graded simulations

Laterally-graded mirrors are not practical except possibly for very low energies (UV or lower). A truly laterally-graded construction would require continuous depth changes for layer pairs. However, a few simulations were completed to show the extreme broadbanded reflectance of such a mirror if depth of layer pairs could be controlled as a point function.

This broadband characteristic suggests a strong connection between frequency-independent electromagnetic (EM) antenna design and the design of broadband multilayers. It is well known[2] in EM antenna theory that if radiating surfaces can be constructed using angles as the exclusive design parameter, the radiation pattern for such an antenna will be independent of frequency. This criteria says nothing about the antenna gain magnitude. True frequency independence implies an infinitely large structure. However, the criteria is still very effective in the design of finite-sized EM antennas as long as an angular variable is a dominant parameter. Examples of EM structures exhibiting broadband characteristics are spirals and log-periodic arrays.

The laterally-graded model used for this study is shown in Figure 3. One layer-pair depth was used as a reference. All reflecting surfaces were then described using the angle α and d_o. The incident wave was divided into N rays, uniformly spaced along the flat surface of the mirror, and the complex reflection coefficients were calculated for each ray and added together. The reflectance was then calculated as the square of the magnitude of the complex coefficient.

Figure 5 shows a plot of reflectance vs. energy for $\alpha = 0.05°$for two mirror widths (n=50, n=100). The high energy cutoff is a result of selection of a non-zero value for the reference layer pair (d_o in Figure 4). $d_o = 24$ **Å** was used in these simulations.

[2]V. Rumsey, *Frequency Independent Antennas*, Academic Press, New York, 1966

Figure 5(a)
N=50

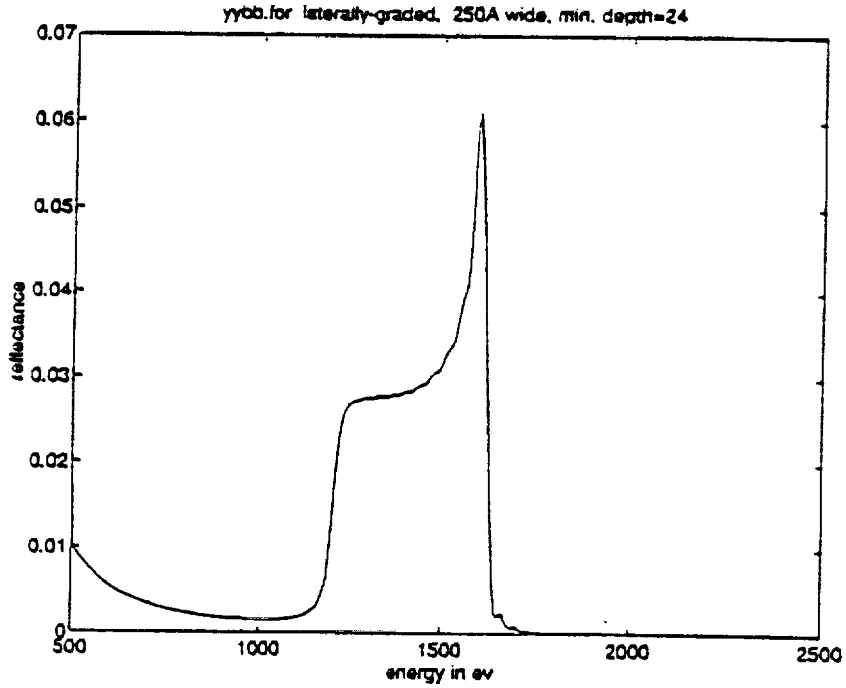


Figure 5 (b)
N = 100

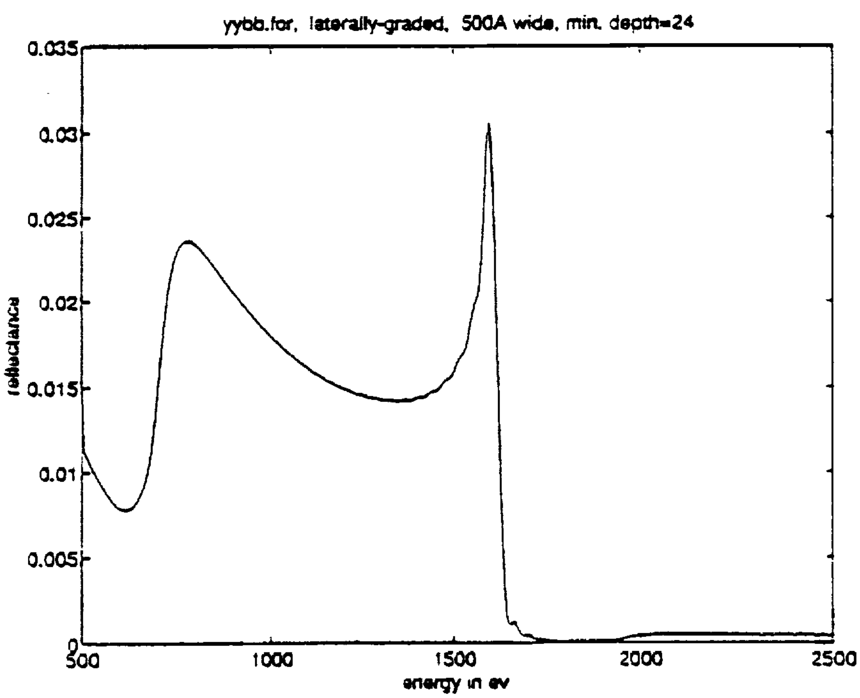


Figure 5. Laterally-graded mirror response, $\alpha = 0.05°$.

Log-periodic simulations

The log-periodic rule for determining systematic changes in layer-pair depths can be expressed with parameter t found in equation 2. In this series of simulations,

$$t = d_1/d_o$$

was used with d_o = 20**Å**. d_o is the initial-layer depth and d_1 is the second layer depth and was required to be larger than 20**Å**. Therefore $t > 1$ and indicates that the initial d-spacing (smallest) is located at the mirror substrate. The same general result occurs when $t < 1$ is used (largest-to-smallest d, beginning at substrate). For a second layer thickness d_1 = 22**Å**, t = 1.1. Similarly, t = 1.25 corresponds to d_1 = 25**Å** (d_o = 20**Å** in all cases). Subsequent layer thicknesses are determined by repeated multiplication of the parameter, t. For example, the thickness of the nth layer would be $d_n = d_o t^n$.

With this model, $d_1 - d_o$ is the minimum increase in layer thickness. The simulation series for log-periodic configurations assumed $d_1 - d_o$ = 2**Å**, 3**Å**, 4**Å**, and 5**Å** which correspond to t values of 1.10, 1.15, 1.20, and 1.25, respectively. A nominal maximum (last) layer-pair depth of 35**Å** was chosen for all cases in order to provide a basis of comparison among the simulations. Consequently, the log-periodic model consists of repeated blocks of a small number of log-periodic layers. For example, when t = 1.2 and d_o = 20**Å**, the 4th layer-pair thickness is calculated as $d_4 = 20\ (1.2)^3 = 34.56$**Å**. Therefore, a log-periodic block of four layer-pairs was repeated ten times to obtain 40 layer pairs.

In addition to the series of simulations just described, t = 1.0141 was used to represent a near-continuous log-periodic case corresponding to the non-realizable verification calculation shown in Figure 4.

The results of log-periodic simulation series can be seen in Figures 6(a)-6(e). All values of t (excluding t = 1.0141) produced multiple peaks of reflectance. The largest reflectance peaks tend to be located at higher energies as t increases. Similarly, peak values of reflectance increased with increasing t. However, the number of different layer-pair thicknesses decreases for rising values of t. The number of layers in a block can be shown to be the most important parameter for increased reflectance magnitudes as well as number of peaks. At t = 1.25, the three-layer response is very similar to the reflectance of depth-graded mirrors where the number of different thicknesses in a basic block is very small.

A very interesting result is that in all cases is ($t \geq 1{,}1$) the multiple reflectance peaks are approximately evenly spaced over energy. This characteristic, if perfectly uniform spatially, would exhibit the following log-periodic relationship.

$$\log (E_2) = \log (E_1) + \log (t) \tag{3}$$

Where E is energy for t = 1.25 and the largest maximum at 1515 ev (see Fig. 6(e)), the adjacent peaks "should" be located at 1892ev and 1210ev. These values miss the measured values by 6% and 14%, respectively, indicating that the process is not perfectly log periodic.

This simulation series was not pursued past this point since, again, implementation requires fractional angstrom values for most layer-pair thicknesses. Moreover, the depth-graded models provide similar results as well as other advantages.

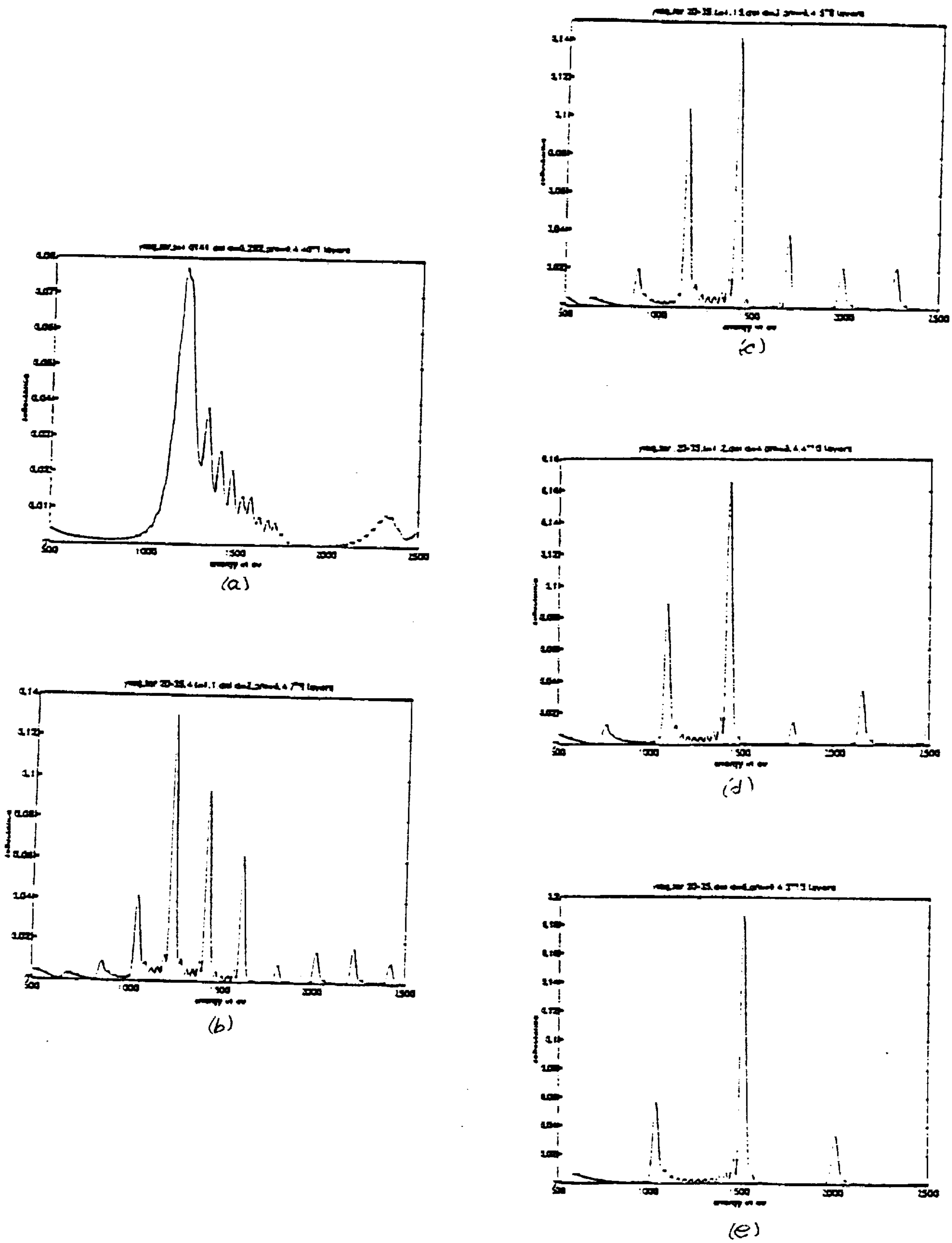


Figure 6. Log-periodic mirror response as a function of increasing t parameter.

Depth-graded simulations

The rule determining the layer-pair thicknesses for depth-graded mirrors is to simply add a specified amount, Δ, to the thickness of the previous layer-pair (or, subtract Δ from the previous thickness). The verification model (results in Fig. 4) utilized Δ = 0.08125Å which is totally unrealistic.

Several series of simulations were produced for depth-graded mirrors.

Series 1

In series 1, reflectances were calculated for the discrete Δ values (in angstroms) 0.25, 1, 2, 3, 4, and 5. As in the log-periodic case, blocks of depth-graded layer-pairs were repeated to obtain approximately 40 total layers. The d-spacings per block ranged from 20Å to a maximum of either 35Å or 36Å. Note that the number of different layer-pair thickness per blocks decreases as Δ increases.

Figure 7 shows reflectance calculations (vs. energy) for the six chosen values of Δ. Multiple peaks in the response appear, somewhat uniformly spaced, covering the entire energy range from 1000 ev to 2500 ev. However, the most significant peaks are contained between about 1200 ev to approximately 1500 ev.

The most interesting characteristic of these curves is that the largest magnitude peak for all values of $\Delta \geq 1$ is always centered at an energy easily relatable to the average of the pair thicknesses in the basic block. In illustration, consider Figure 7 (f) where Δ = 5Å. The layer-pair thicknesses are 20, 25, 30, and 35Å's with an average, $\langle d \rangle$ = 27.5Å. Interpolation yields an energy of 1405 ev for the maximum peak. If a d-spacing is calculated for this energy using the

Bragg equation for a uniform mirror, $d_c = 27$Å, this sequence is summarized in the equation below.

$$d_c = \langle d \rangle - 0.5 \tag{3}$$

This relationship was found to hold for energies through 2500 ev.

Note that the simulations shown in Figures 7 (d) and 7 (f) have their highest valued peaks at approximately the same energy. Both cases have $\langle d \rangle = 27.5$. Finally, the three cases (excluding $\Delta = 0.25$) remaining each have $\langle d \rangle = 27.5$, yeilding highest peaks at a common energy as expected.

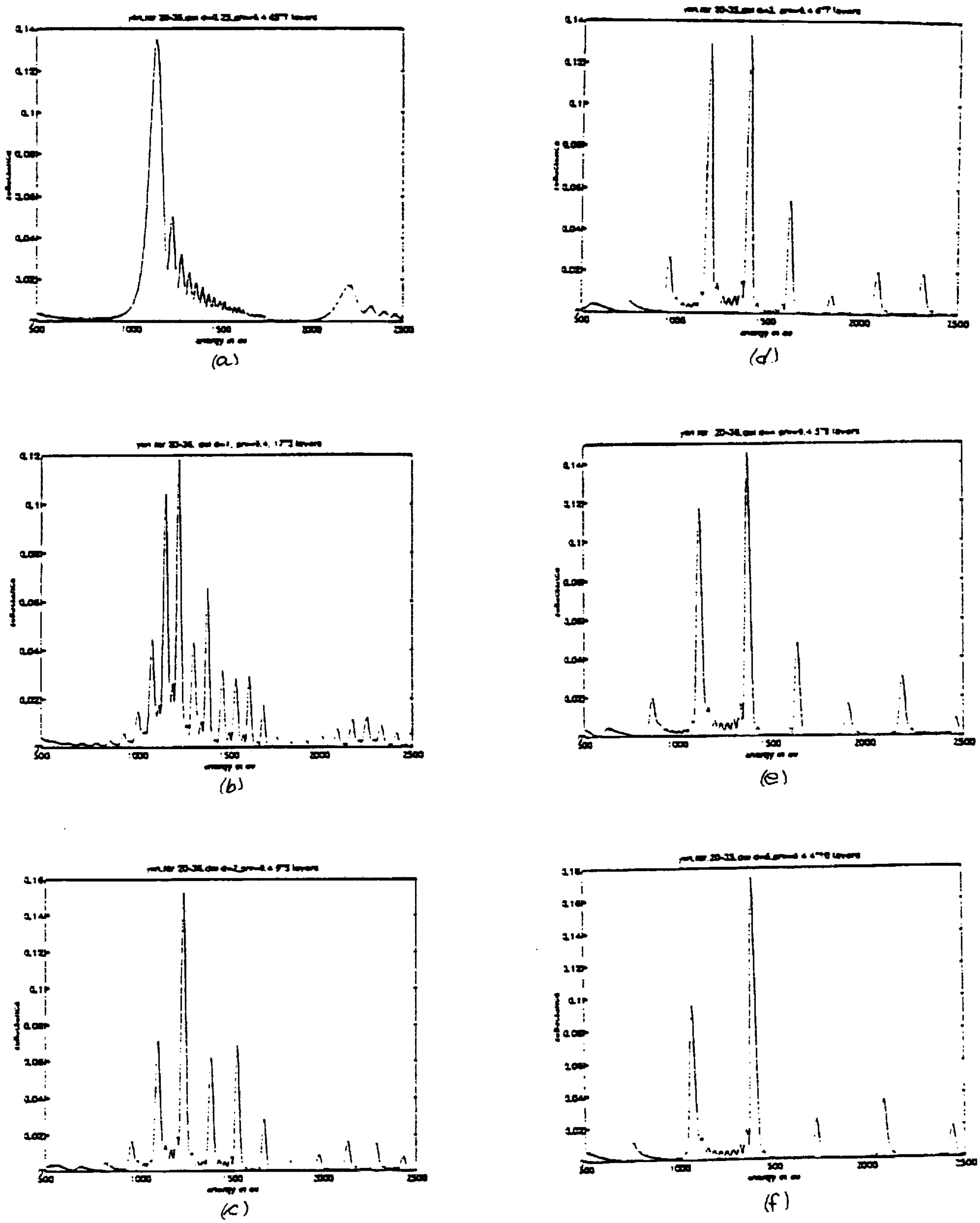


Figure 7. Depth-graded mirror response as a function of increasing change, Δ, in layer-pair thickness.

Series 2

In the simulation just discussed, the thickness change, Δ and the number of layer-pairs per basic block changed. Series 2 consists of simulations for a fixed Δ but the number of pairs per block change. Table 1 contains the parameters used in the Series 2 simulations. The results are shown in Figures 8 and 9 for Δ = 5**Å** (2, 3, and 4 layers/block) and Δ = 4**Å** (3, 4, and 5 layers/block), respectively.

The most significant finding from Series 2 simulations is that the reflectance increases for decreasing number of layers per block. For comparison, Figure 10 shows the reflectance for the two layers/block, Δ = 5**Å** case (Figure 8(a)) beside that of a 40 layer uniform mirror where d = 26**Å**. This comparison shows essentially the same shape reflectance curve for the two layers/block depth-graded mirror and the uniform mirror.

Table 1 Parameters for Series 2 Simulations

Figure	Δ Å	layer thicknesses in basic block; <d>	layers per block	total layers
10(a)	5	24,29; 26.5	2	40
10(b)	5	22,27,32; 27	3	39
10(c)	5	20,25,30,35; 27.5	4	40
11(a)	4	24,28,32; 28	3	39
11(b)	4	22,26,30,34; 28	4	40
11(c)	4	20,24,28,32,36; 28	5	40

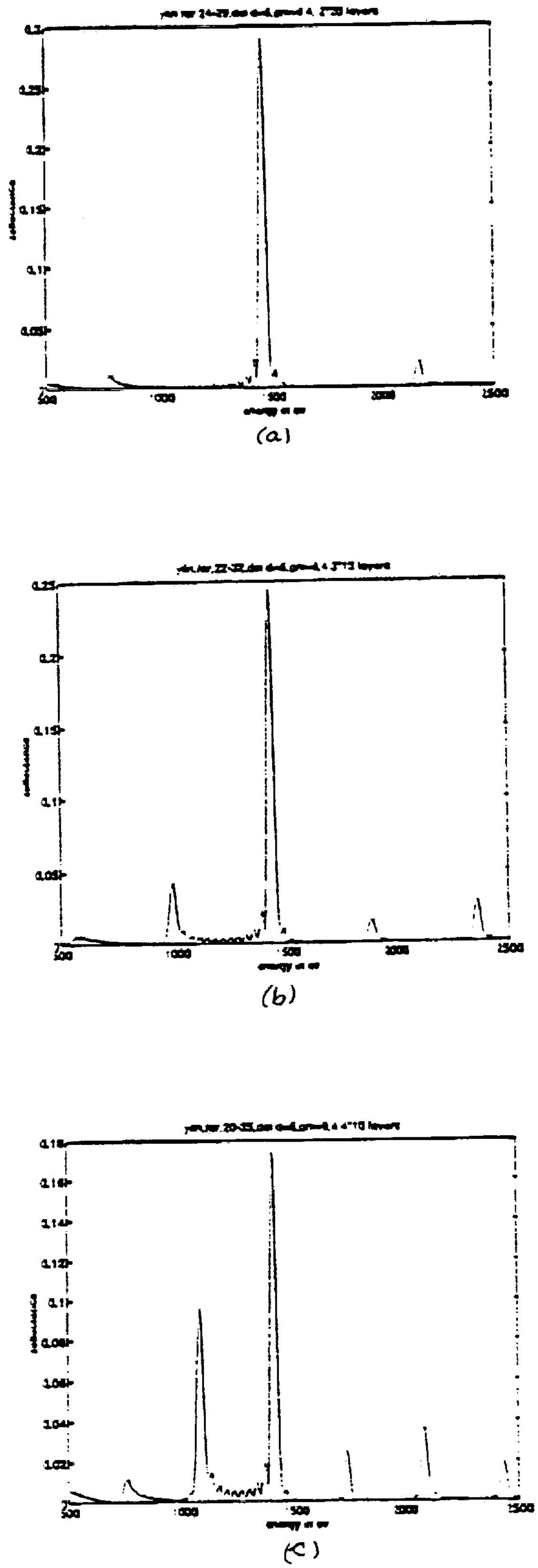


Figure 8. Depth-graded mirror response as a function of increasing number of layer-pairs per block (fixed $\Delta = 5Å$).

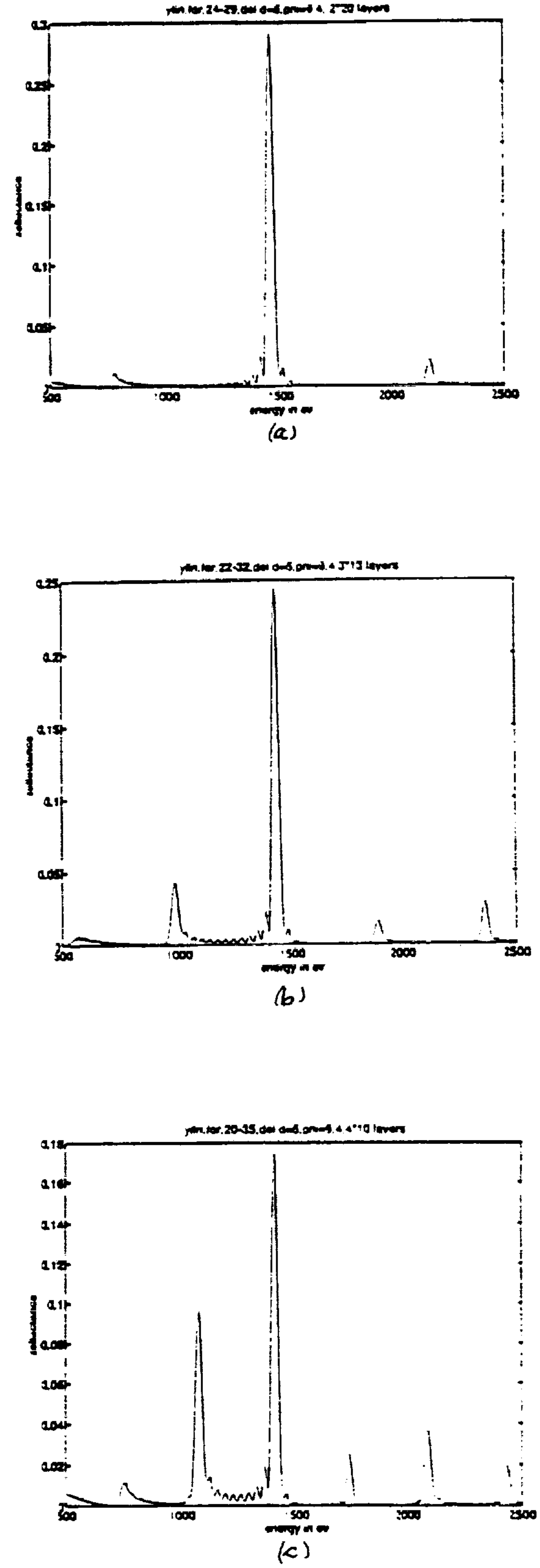


Figure 9. Depth-graded mirror response as a function of increasing number of layer-pairs per block (fixed $\Delta = 4$Å).

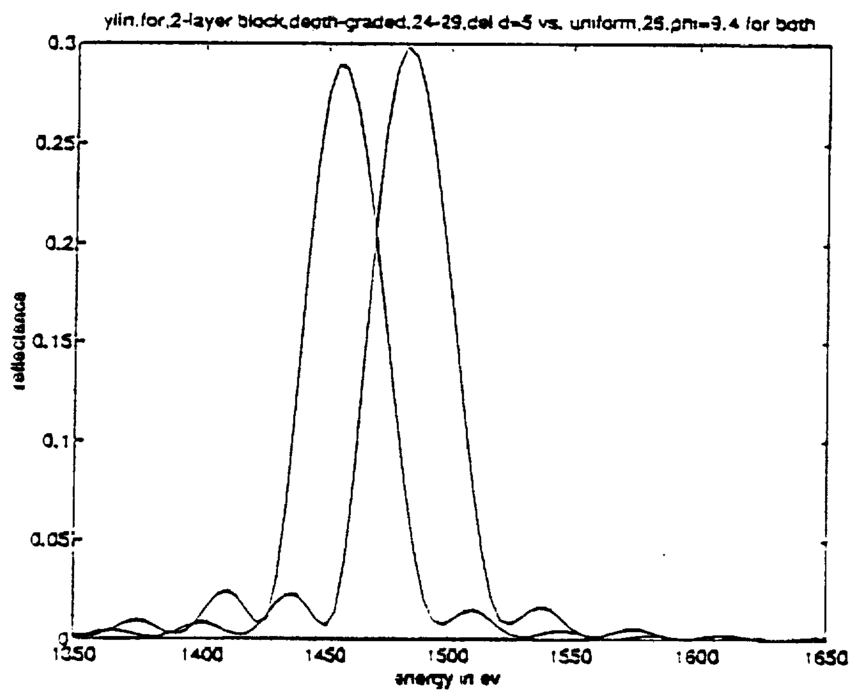
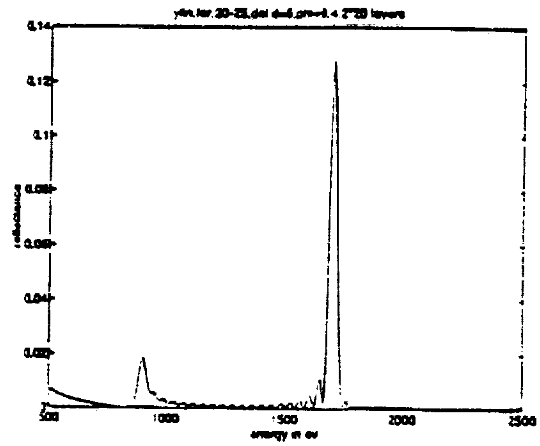


Figure 10. Comparison between a depth-graded, 2-layer per block mirror (on left) and a uniform mirror (on right).

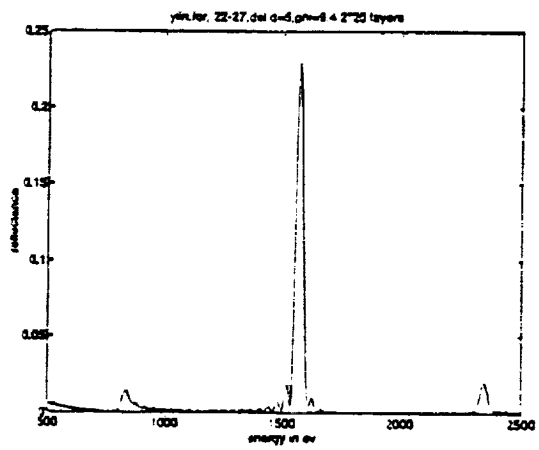
Series 3

The Series 3 simulations consist of response comparisons for three separate two layers/block depth-graded mirrors each with $\Delta = 5\text{Å}$. The only difference among the three cases is the layer thickness choices. One simulation uses thicknesses (Å) of 20 and 25. Another has 22 and 27 while the third thicknesses (Å) are 24 and 29. The results are shown in Figure 11.

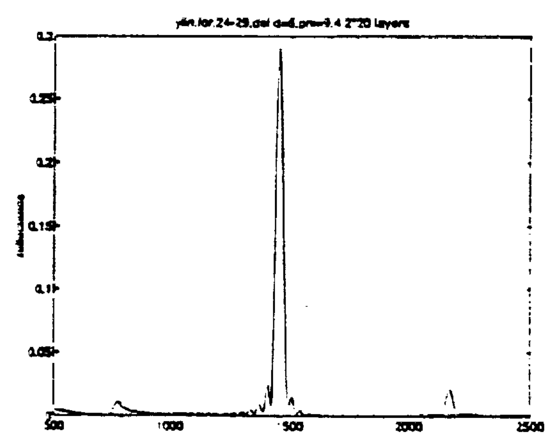
For these cases, larger thicknesses tend to yield higher reflectances. This feature has not been thoroughly investigated and may not be true over all energy ranges, angles, etc. Conversely, the implication shown in Figure 11 that the location of highest resistivity peaks can be controlled to some degree again presents itself.



(a)



(b)



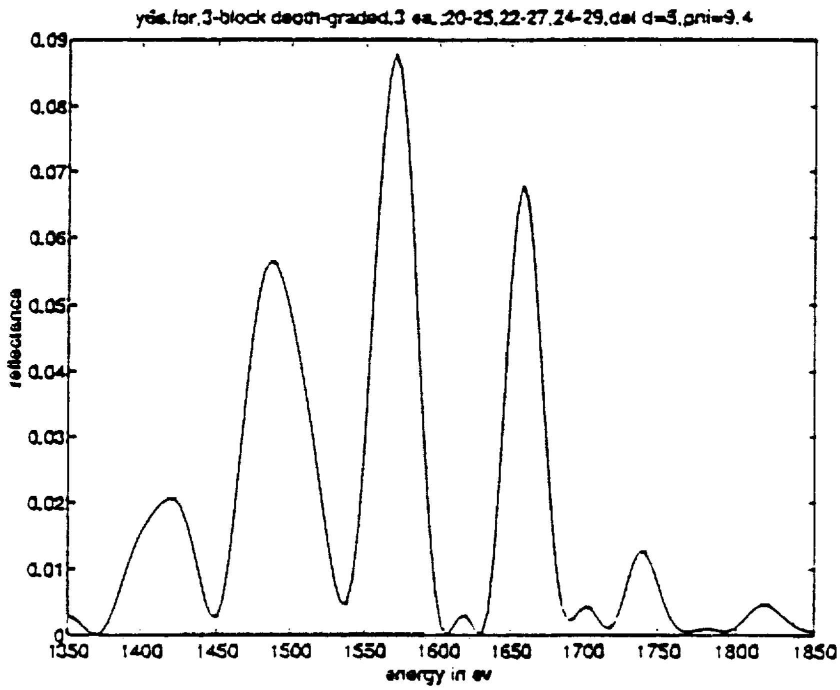
(c)

Figure 11. Response from 2-layer per block depth-graded mirrors with fixed $\Delta = 5$Å as a function of increasing thickness of the "first"layer.

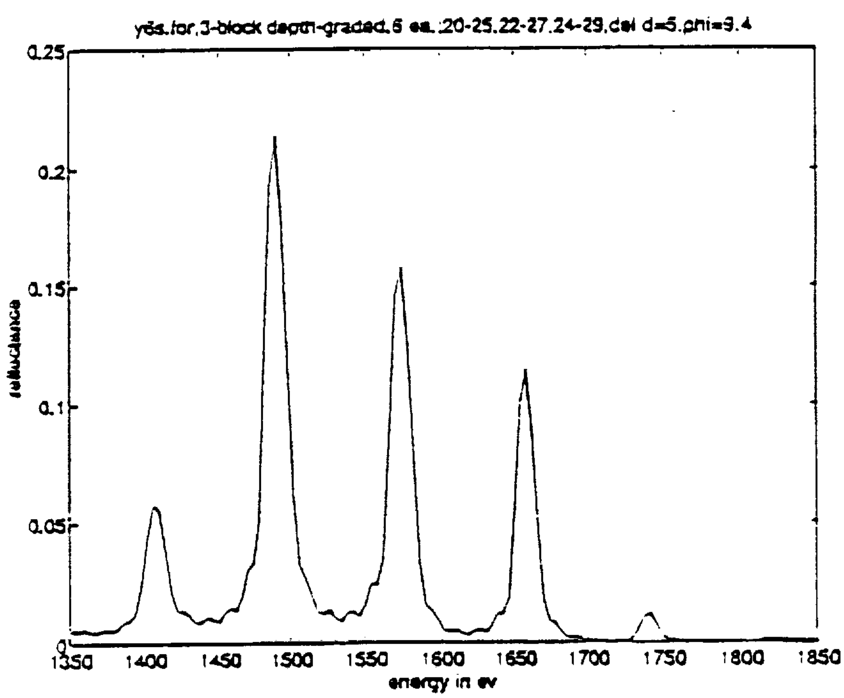
Series 4

The final simulation consists of three distinct depth-graded blocks, combined into a composite mirror on a single substrate. Each block consists of two layer-pairs with Δ = 5Å. Each block consisted of the two layers repeated three times. Then, the entire 3-block group was repeated. Layer thicknesses in the blocks were 20-25, 25-30, and 30-35. Calculated reflectances are shown in Figure 12(a) for 54 total layers (group repeated 3 times) and in Figure 12(b) for 108 total layers.

Three separate reflectance peaks were produced in both cases. As expected, the thicker mirror (108 layers) produced higher reflectances and narrower bandwidth than the "thin" (54 layer) mirror. However, the effective bandwidth is at least three times that from a uniform mirror in the same energy range.



(a)



(b)

Figure 12. Composite 3-block depth-graded mirror response. Block layers (Å): 20-25, 25-30, 30-35. (a) 54 total layer pairs (b) 108 total layer-pairs.

SUMMARY OF PARAMETRIC STUDY RESULTS

Laterally-graded models exhibited very broadband reflectances but were deemed impractical for fabrication at x-ray wavelengths.

Log-periodic simulations yielded enhanced broadening only with impractical layer-pair thicknesses. As differences in layer-pair thicknesses increased, the reflectance pattern, as a function of energy, consisted of multiple, non-overlapping peaks. However, even with large thickness differences, the calculated thickness requirements were impractical for actual fabrication.

Depth-graded simulations exhibited the most interesting results. The reflectance patterns were similar in appearance to those of the log-periodic models. However, since the thickness differences among layer-pairs is fixed in the depth-graded case, fabrication is feasible.

In simulations of depth-graded mirrors, the number of different thicknesses was limited, especially for larger thickness changes, in order to place the reflectance peaks within a reasonably small energy range. This required a mirror configuration consisting of repeated blocks of layer-pair thicknesses. A block was composed of a few layers of different thicknesses defined by linear increase.

Reflectance from repeated-block depth-graded mirrors were very similar to those from uniform mirrors operating in the same energy range. The advantage of any repeated-block depth-graded model is that there can be considerable control over the location (energy) of the major reflectance peak.

Finally, reflectance from groups of different repeated depth-graded blocks yielded an effective bandwidth enhancement. A reflectance peak representative of each block appeared in the response so that even though no peak overlaps occurred, a wider range of energies yielded useful outputs compared with a uniform mirror.

The results summarized here are used in several design simulations, detailed in the next section.

DESIGN SIMULATIONS

The simulations described below are used in attempts to "design" multi-layer mirrors that yield useful reflectances over a range of grazing angles in the energy range 6500 ev-7100 ev, corresponding to a wavelength range of 1.78**Å**-1.88**Å**.

The simulations for single mirrors with simple structures yielded no advantage in bandwidth over uniform mirrors. Therefore, the models discussed below include a depth-graded mirror with three separate repeated blocks and several configurations with more than one mirror on a common substrate. No attempts were made to insure equal total mirror thickness for two- and three-mirror composites since the simulations were for feasibility information.

Design 1

A 3-block depth-graded configuration constituted design 1. Each block consisted of two layers, repeated three times, defined below.

- Block 1: Layer thicknesses of 21**Å** and 26**Å**, repeated 3 times.
- Block 2: Layer thicknesses of 26**Å** and 31**Å**, repeated 3 times.
- Block 3: Layer thicknesses of 31**Å** and 36**Å**, repeated 3 times.
- The entire 18 layer group was repeated 3 times for a total of 54 layers.

The reflectance calculations are shown in Figures 13, 14, and 15. Figure 13 shows results at a single energy, 6800 ev, for varying grazing angle. Note that three peaks are present, one attributable to each of the basic depth-graded blocks. Even though the maximum reflectance is much lower than for uniform or single-block depth-graded mirrors having 54 layer-pairs, the effective bandwidth is significantly increased. This type fabrication is definitely feasible. Figure 14 is a three-dimensional renderings of the reflectance and Figure 15 is the corresponding contour plot.

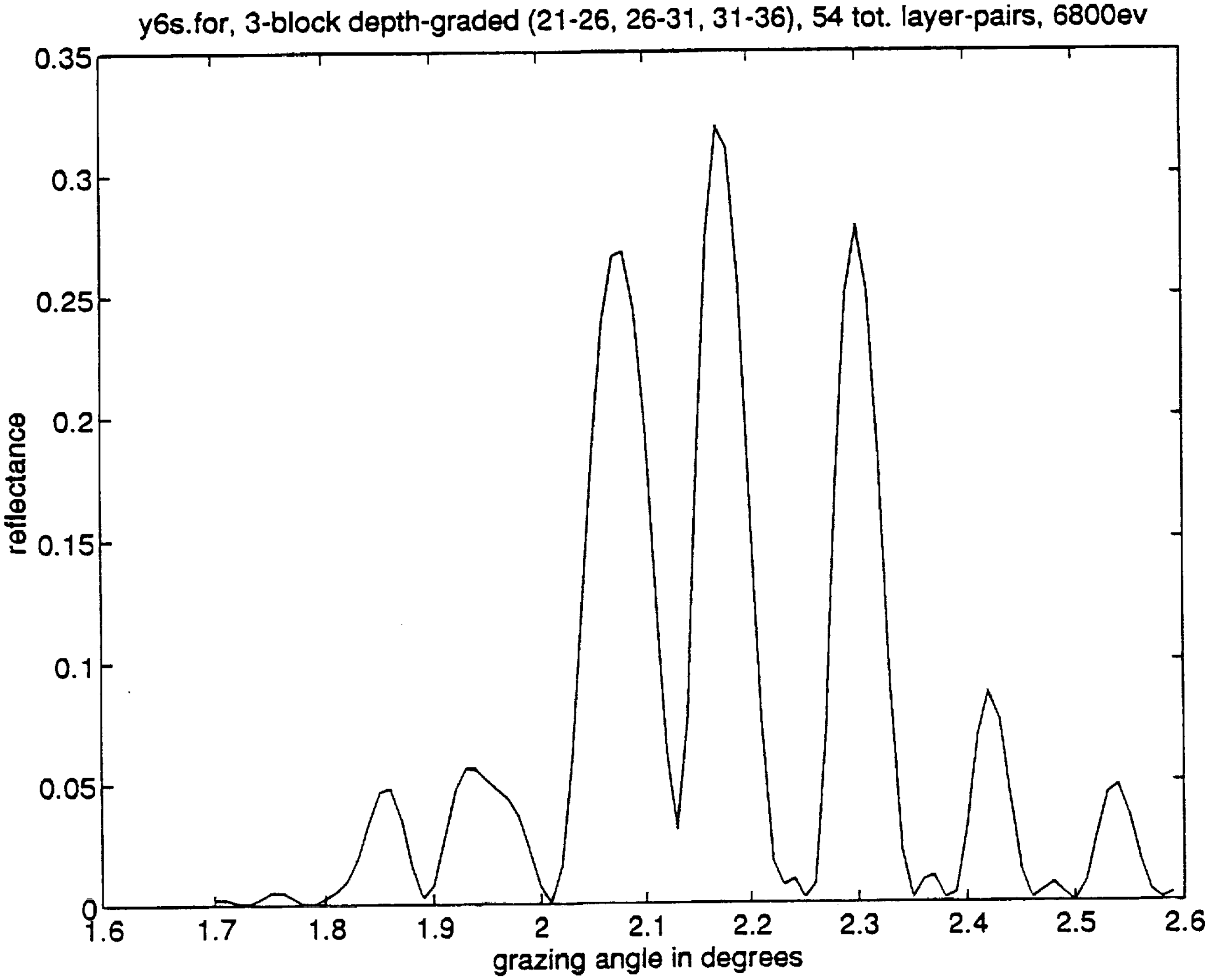


Figure 13: Response from a 3-block depth-graded mirror at an energy of 6800 ev as a function of grazing angle. The 2-layer blocks are (Å) 21-26, 26-31 and 31-36. 54 total layer-pairs.

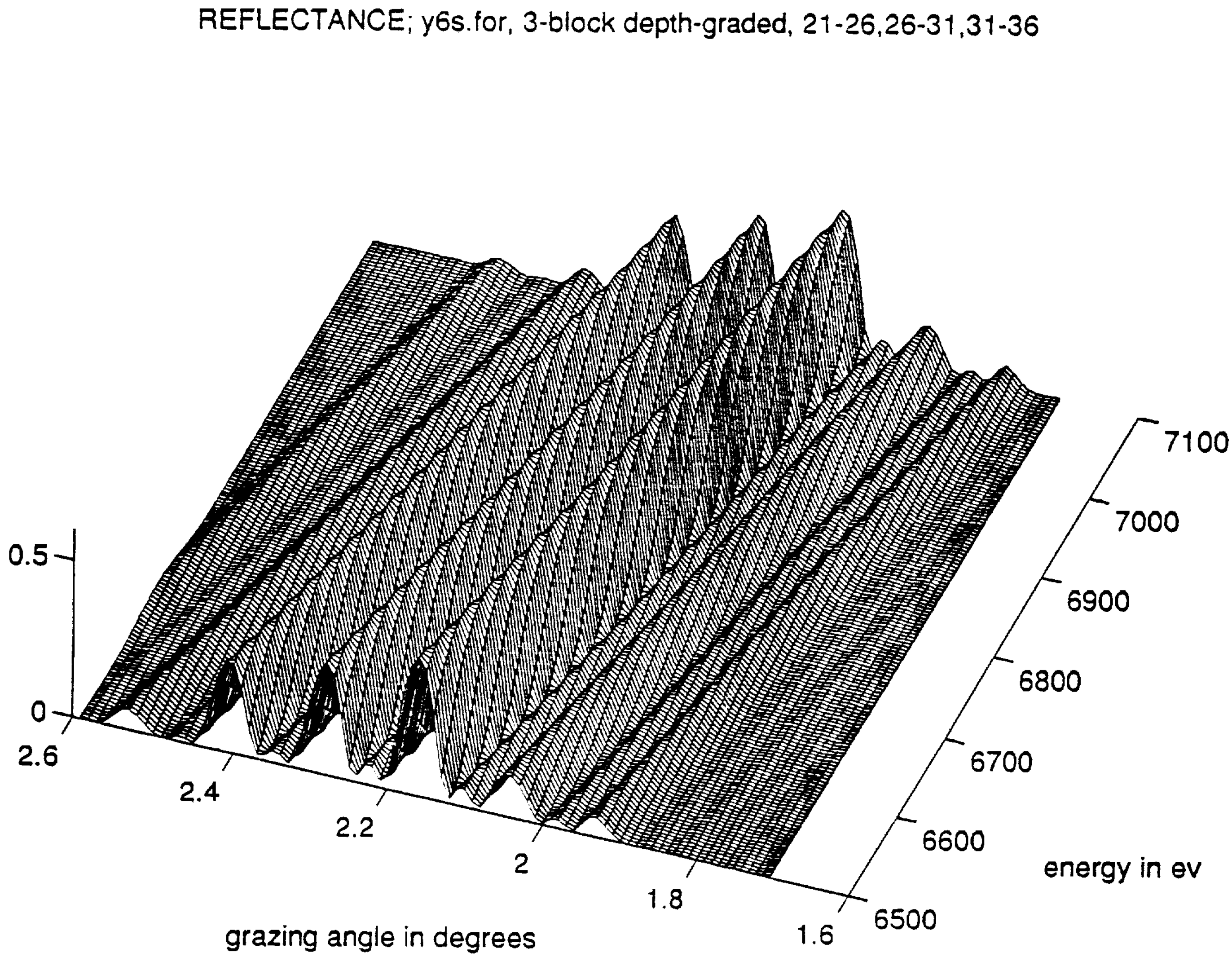


Figure 14: Three-dimensional plot of response from a 3-block depth-graded mirror as a function of grazing angle and energy. The 2-layer blocks are (Å) 21-26, 26-31 and 31-36. 54 total layer-pairs.

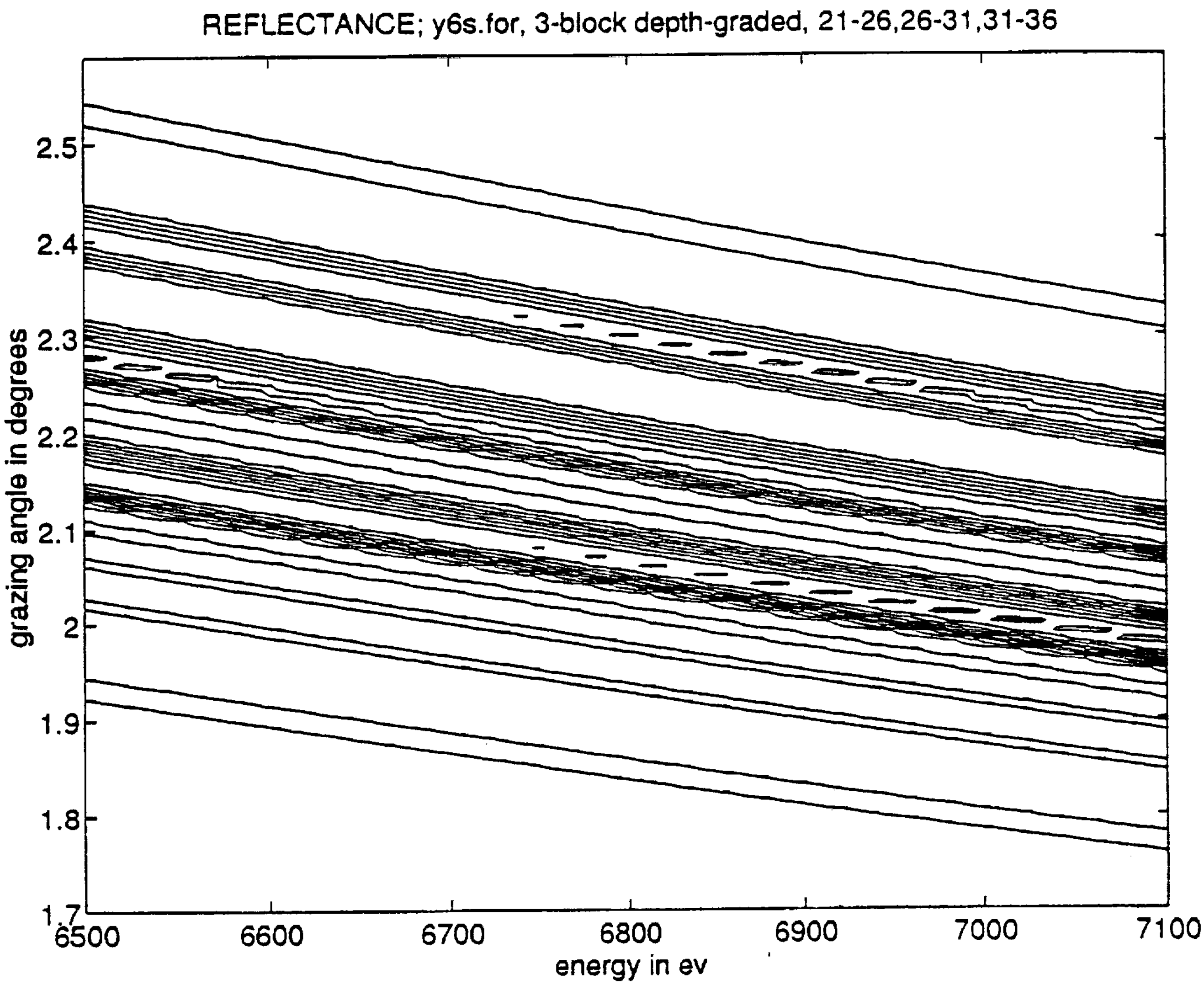


Figure 15: Contour plot of reflectance from a 3-block depth-graded mirror with grazing angle and energy as variables. The 2-layer blocks are (Å) 21-26, 26-31 and 31-36.

Design 2

In this simulation, two uniform mirrors having layer-pair thicknesses 26Å and 31Å, respectively are assumed to be adjacent on the same substrate. Figure 16 shows reflectance vs. grazing angle at 6800 ev for this composite mirror. The two peaks are essentially the same as if the two mirrors were simulated separately. In actual fabrication, the finite size of mirrors must be taken into account. For this model, the "infinite mirror" assumption inherent in the computer programs used gives results that are qualitative in nature. Figure 17 shows the three-dimensional response for design 2.

Compared with design 1, the peak reflectance are higher but the total bandwidth is less.

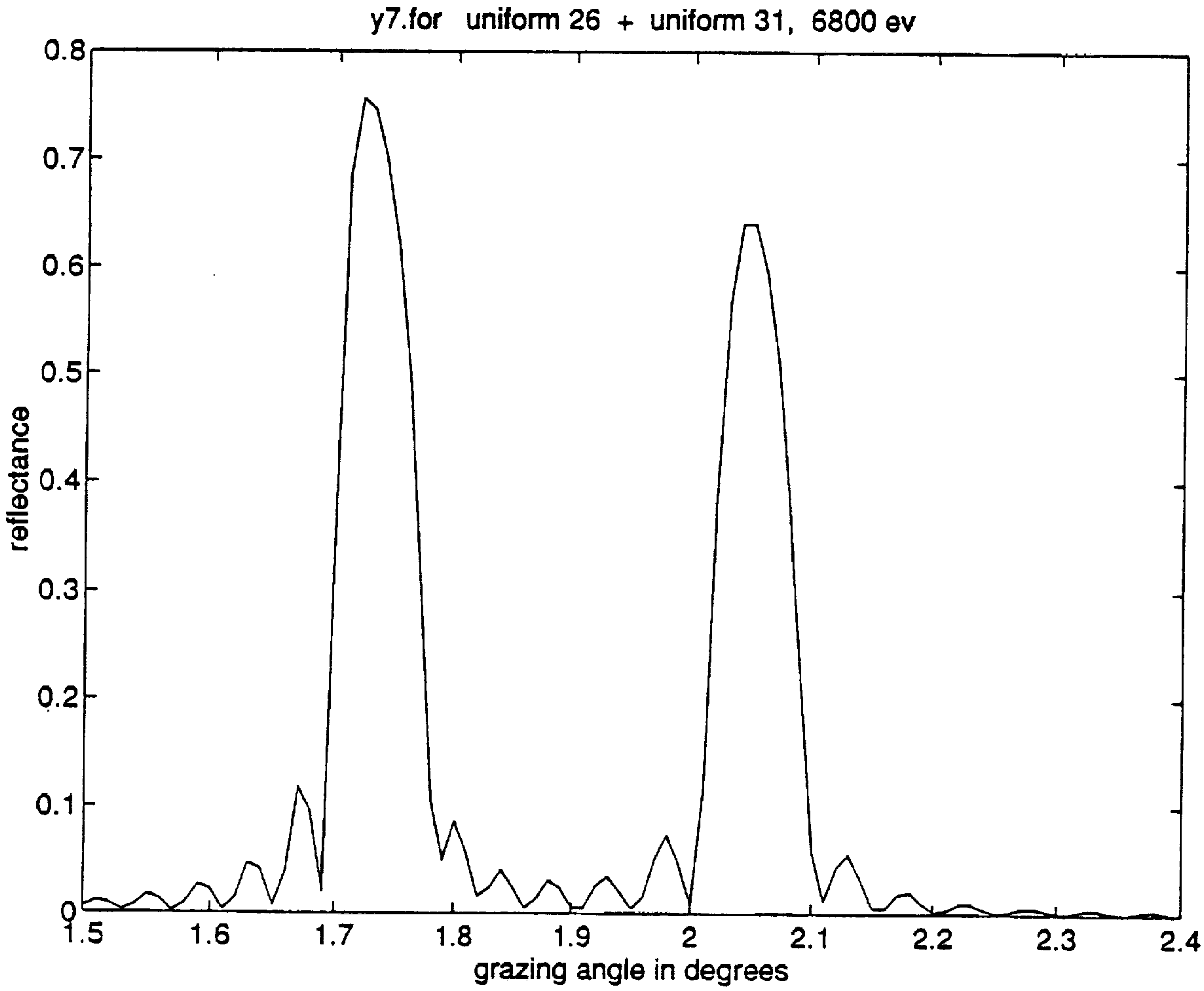


Figure 16: Response from a composite structure consisting of adjacent uniform mirrors (d = 26 Å and d = 31 Å) as a function of grazing angle for fixed energy 6800 ev.

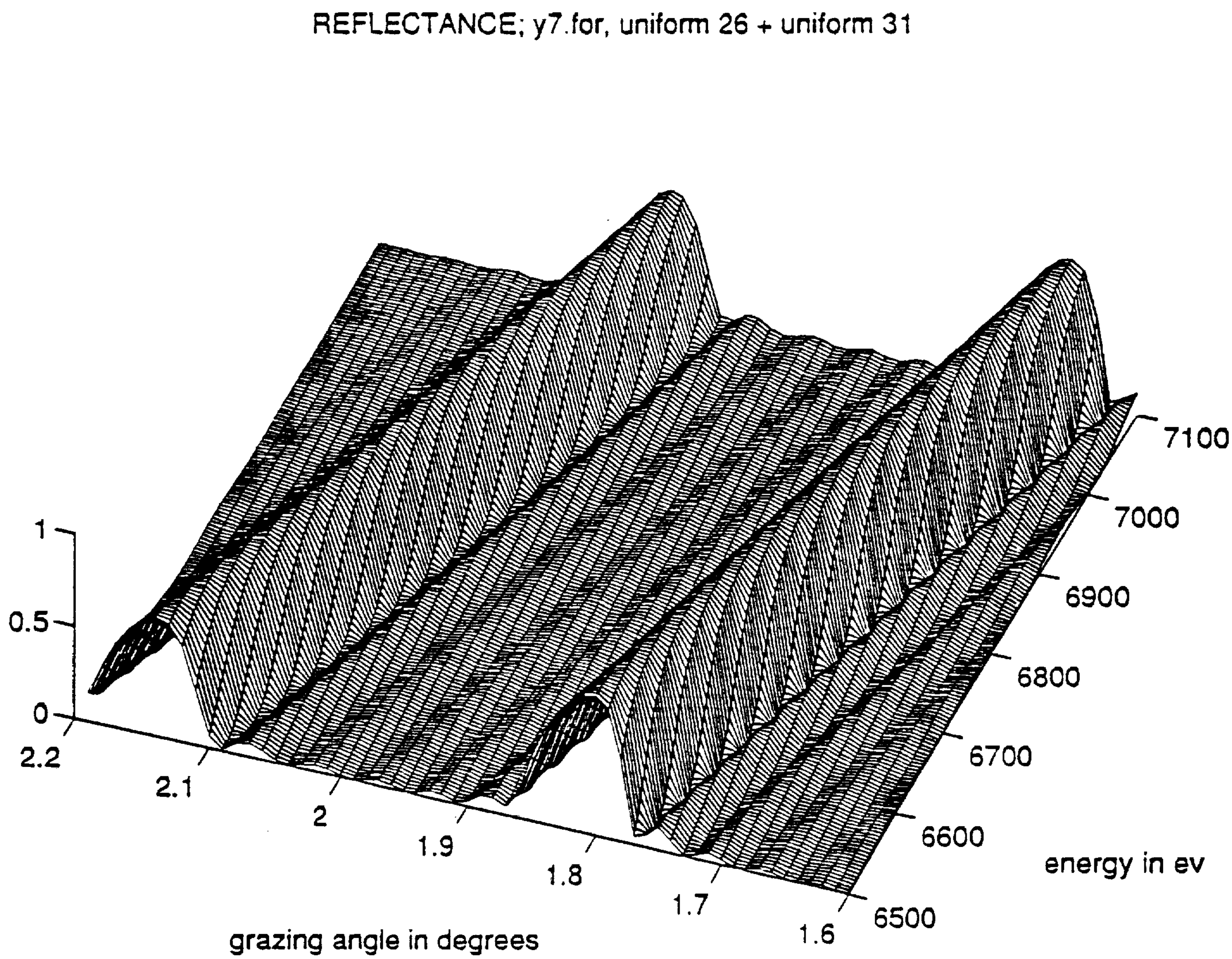


Figure 17: Three-dimensional response from a composite structure consisting of adjacent uniform mirrors (d = 26 Å and d = 31 Å) as a function of grazing angle and energy.

Design 3

The final composite model assumes three adjacent mirrors on the same substrate. Two uniform mirrors, again with 26Å and 31Å layer-pair thicknesses, and a single-block, two-layer (26Å and 31Å) depth-graded model (reflectance is shown in Fig 18) discussed earlier were chosen as the component reflectors. Figure 19 is a three-dimensional plot of the reflectance. Note that the depth-graded response lies between those of the two uniform mirrors.

If conditions were such that uniform layer pairs 26Å thick were desired and feasible but the next higher feasible thickness is 31Å, this example demonstrates the possibility of placement of a reflectance peak between the two "feasible" responses. Construction of the depth-graded model used here should also be feasible since implementation depends only upon the "realizable" uniform layer-pair thicknesses.

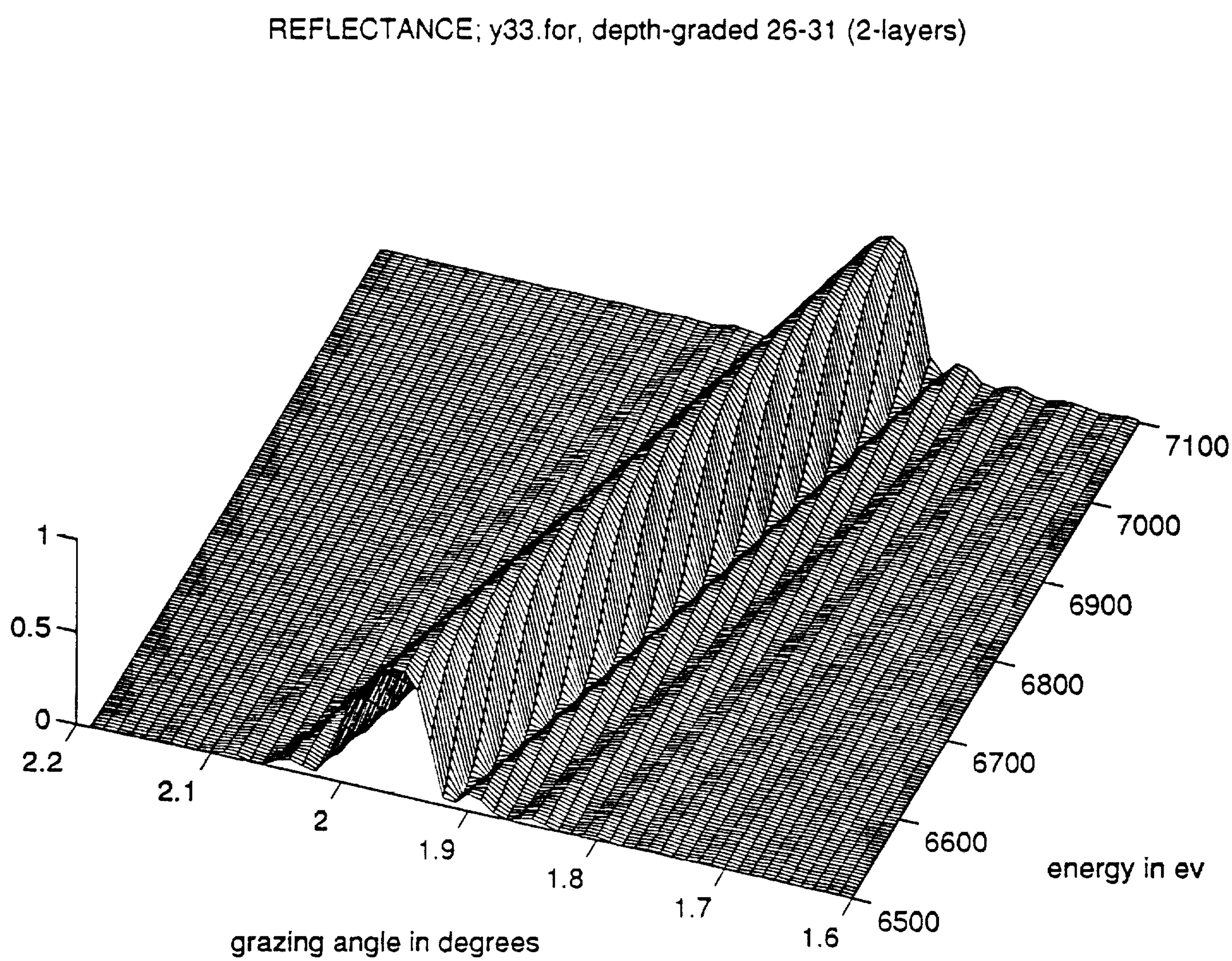


Figure 18: Three-dimensional response from a single-block, 2 layers per block depth-graded mirror as a function of grazing angle and energy. Block thicknesses are 26 Å and 31 Å.

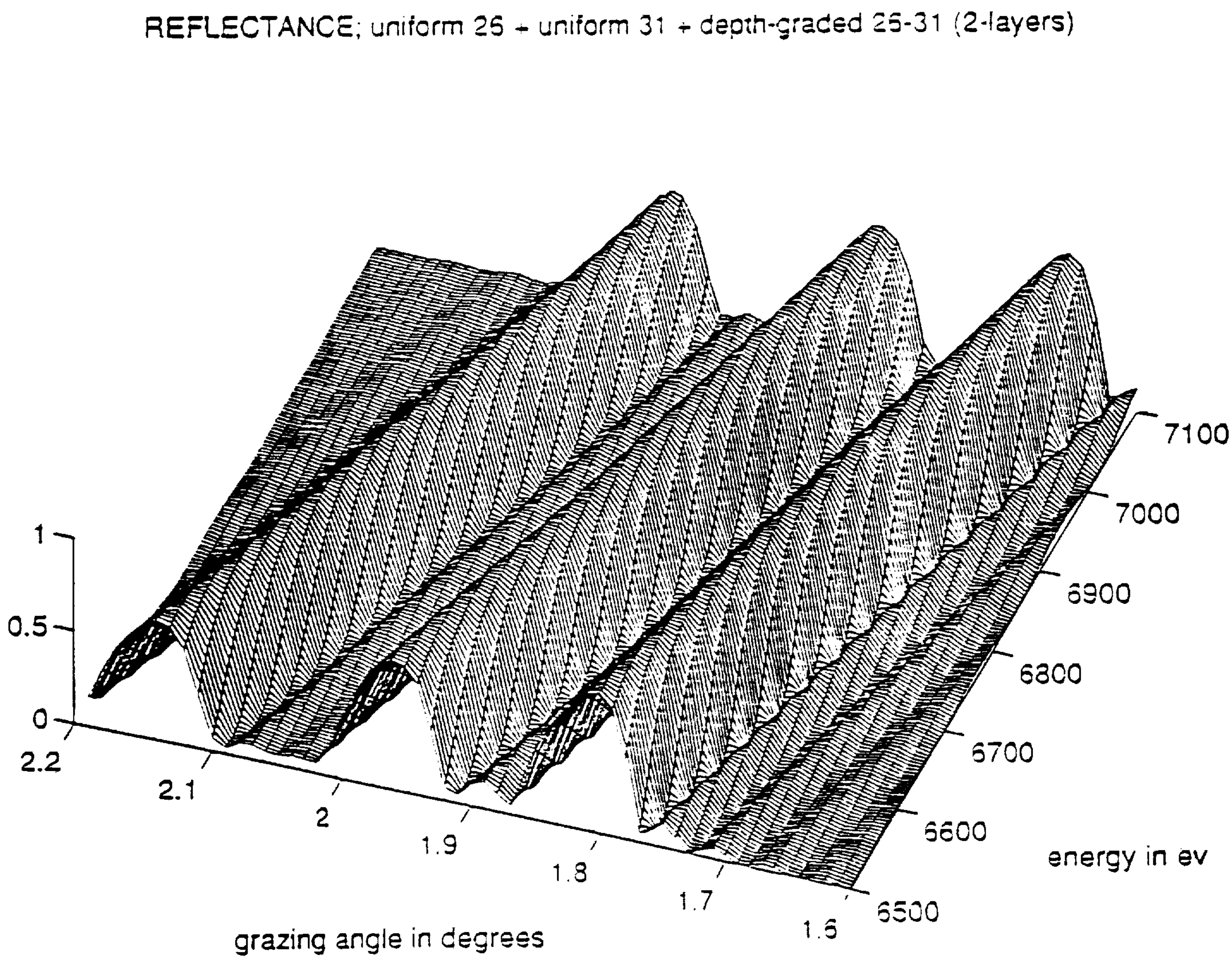


Figure 19. Three-dimensional response from a composite structure consisting of three adjacent mirrors. The mirrors are uniform with d = 26Å, uniform with d=31Å and single-block depth-graded with layer-pair thicknesses 26Å and 31Å. Reflectance is shown as a function of grazing angle and energy.

APPENDIX

Full Size Copies of Selected Figures

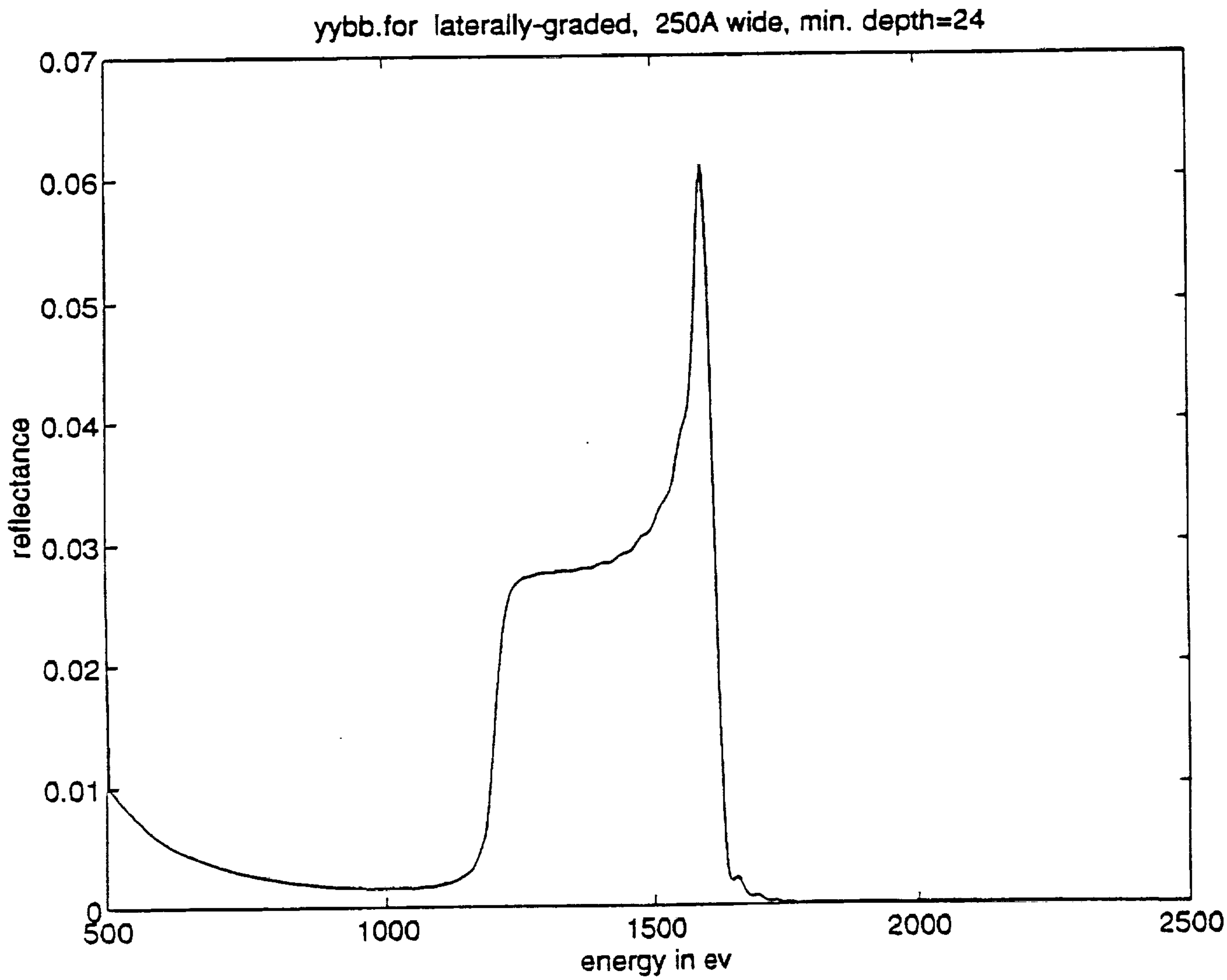


Figure 5(a) Laterally-graded mirror response, $\alpha = 0.05°$. N=50

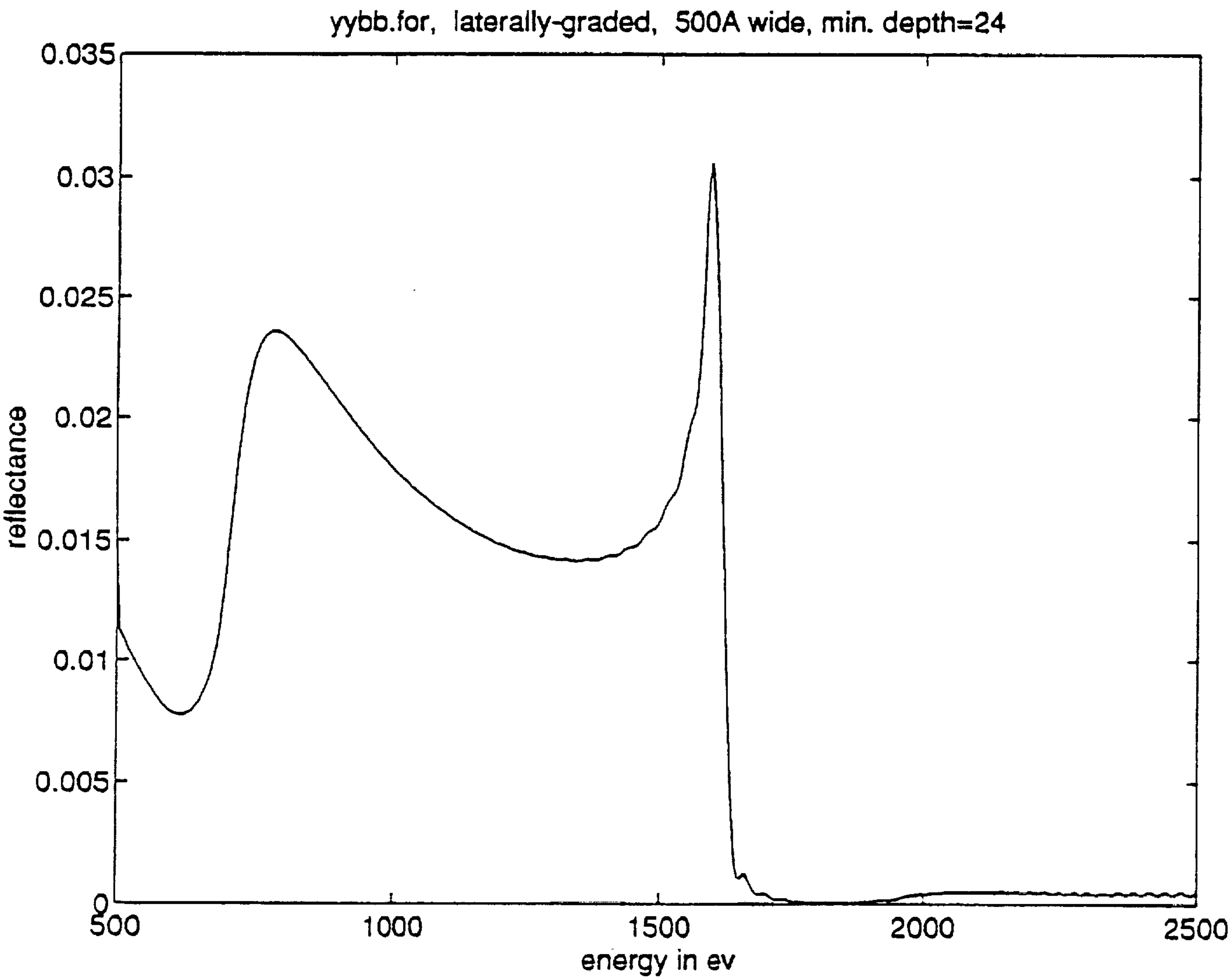


Figure 5 (b) Laterally-graded mirror response, $\alpha = 0.05°$. N = 100

Figure 6: Log-periodic mirror response as a function of increasing t parameter.

Figure 6(a) $t = 1.0141$

Figure 6(b) $t = 1.1$

Figure 6(c) $t = 1.15$

Figure 6(d) $t = 1.2$

Figure 6(e) $t = 1.25$

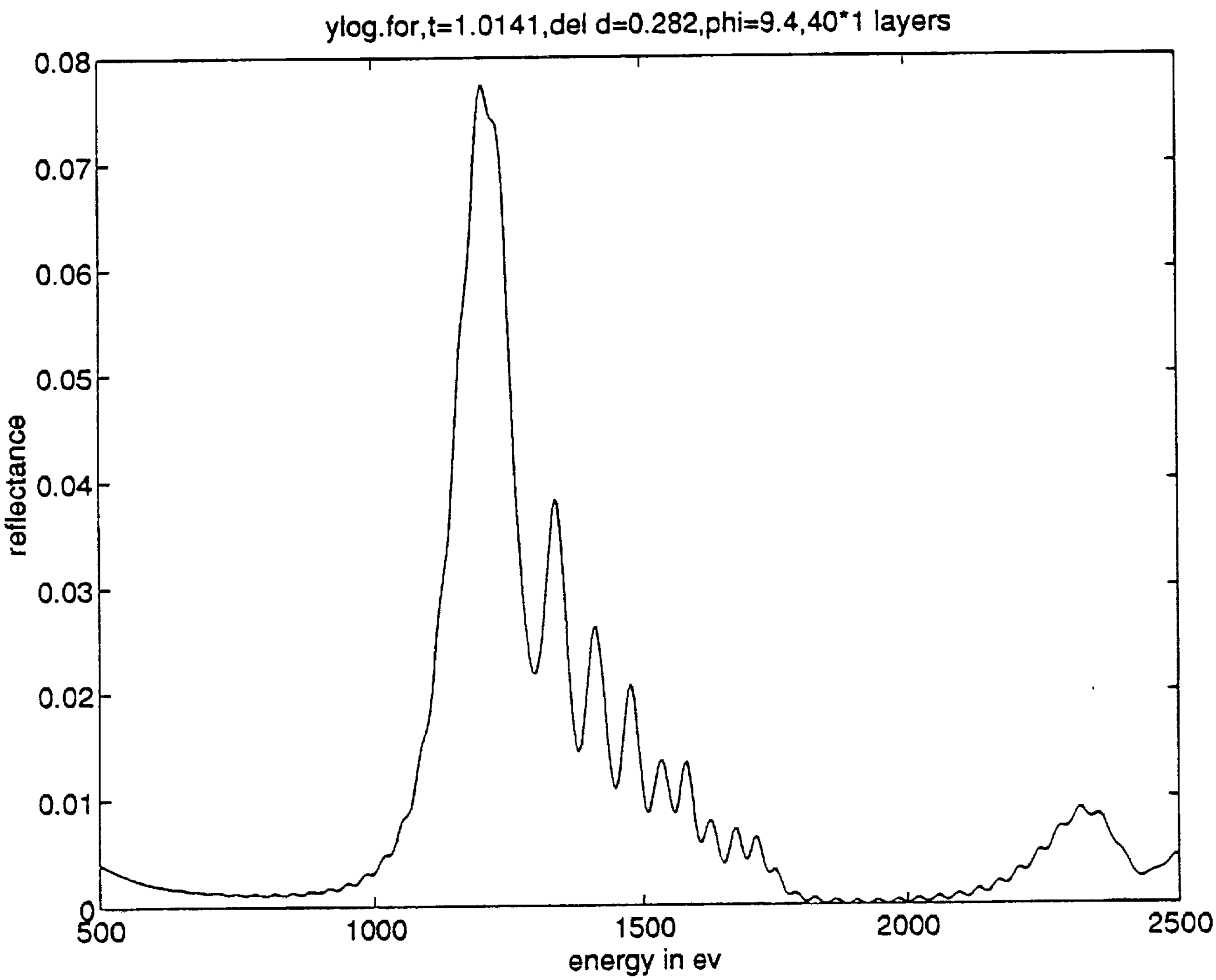


Figure 6(a) t = 1.0141

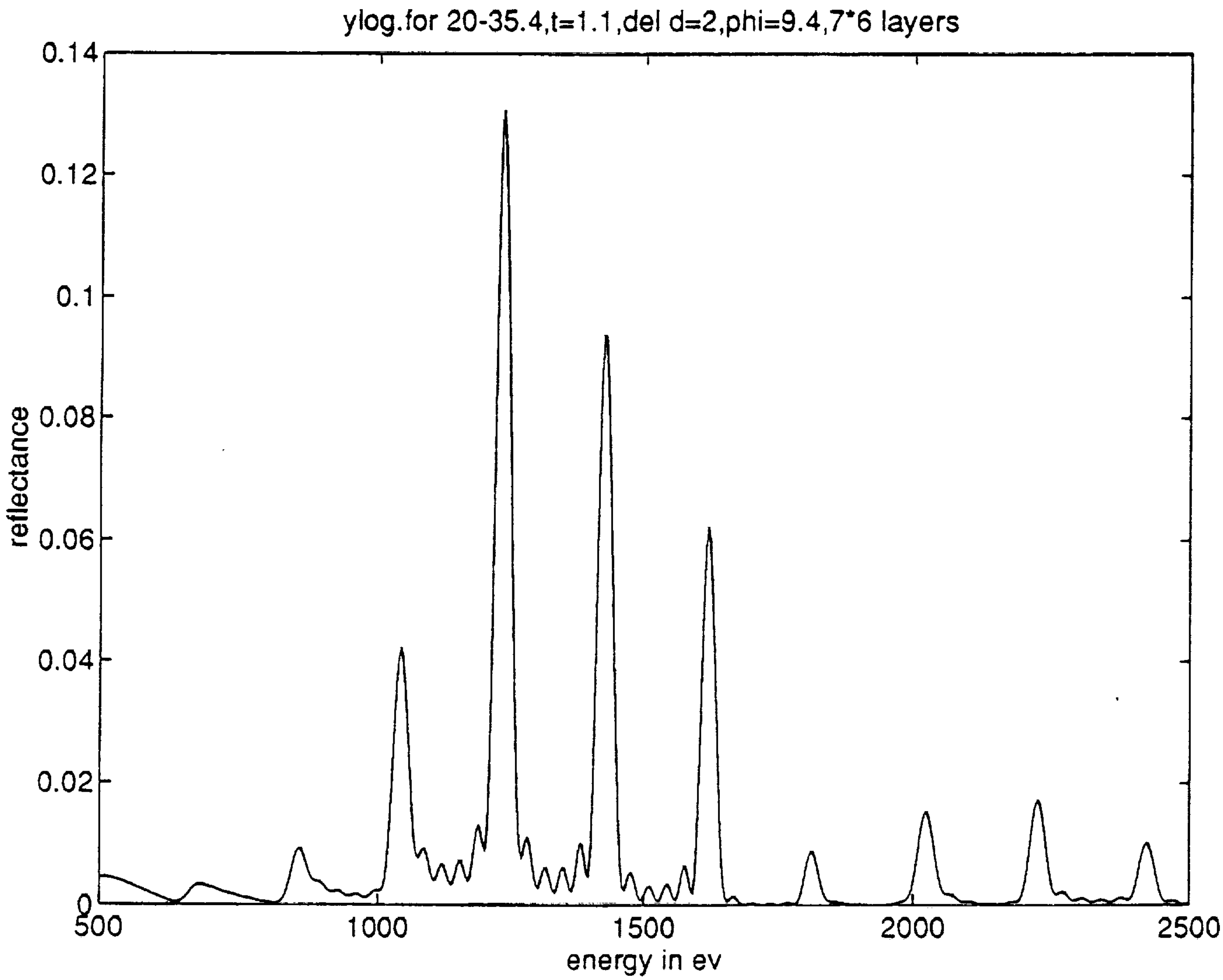


Figure 6(b) $t = 1.1$

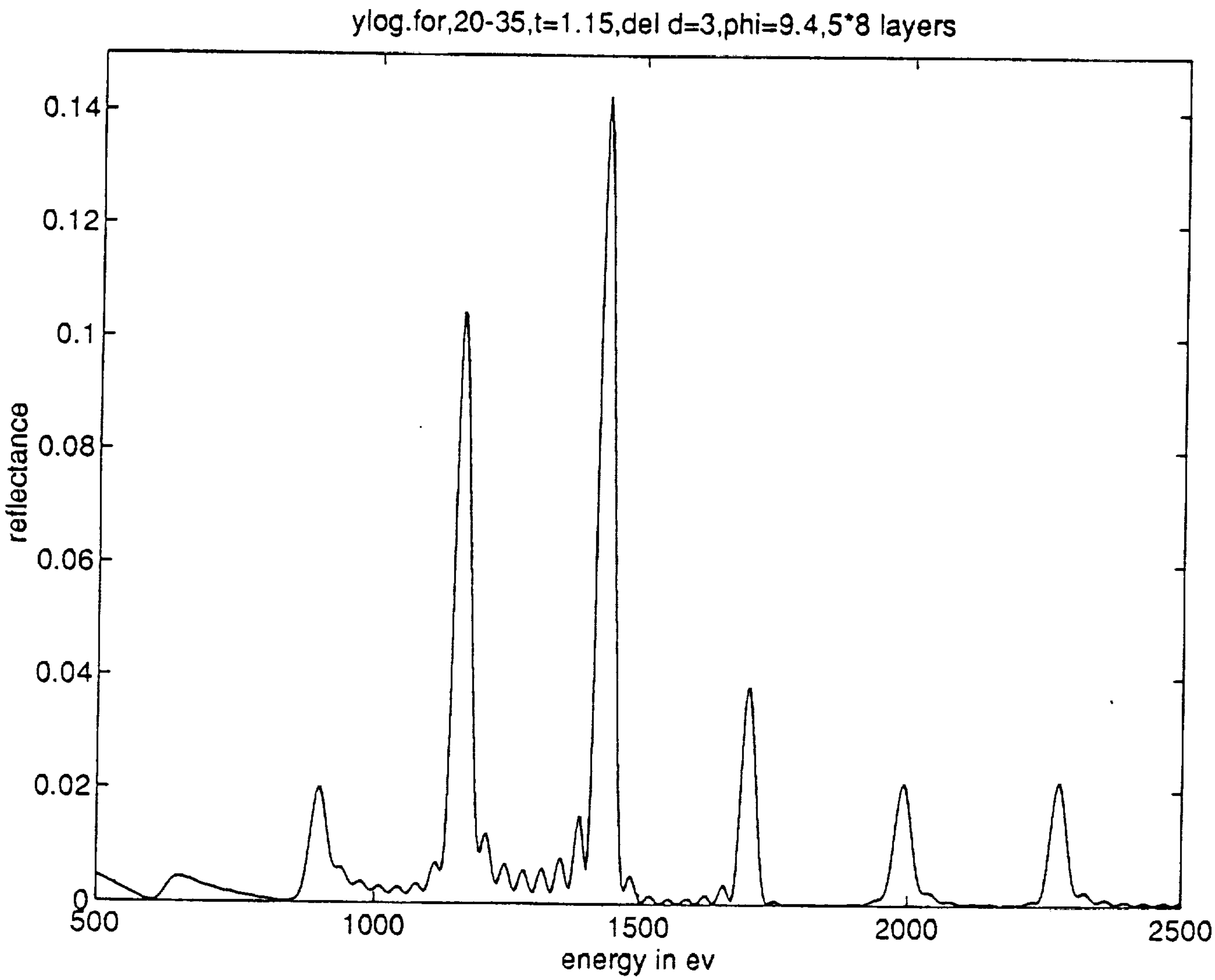


Figure 6(c) $t = 1.15$

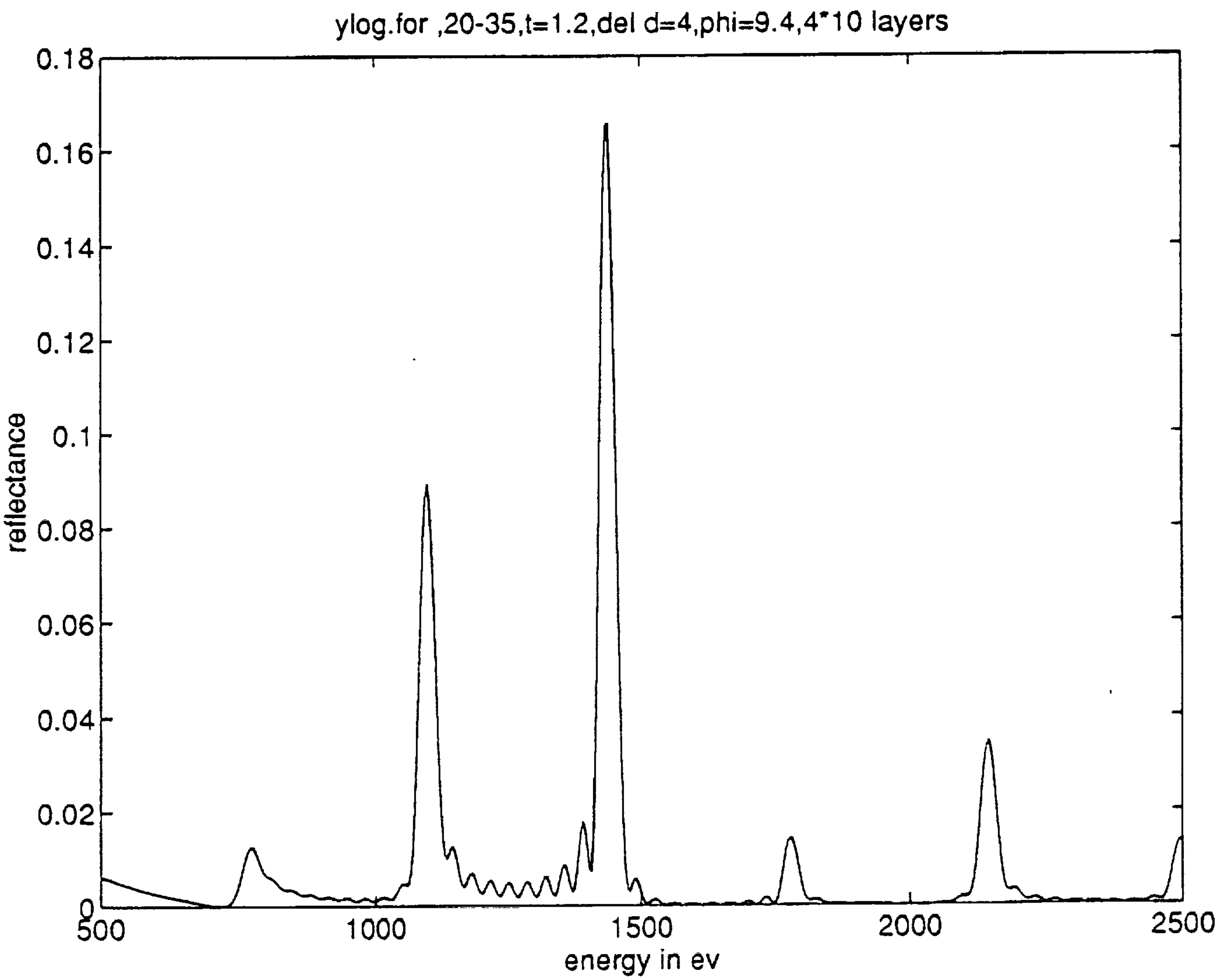


Figure 6(d) $t = 1.2$

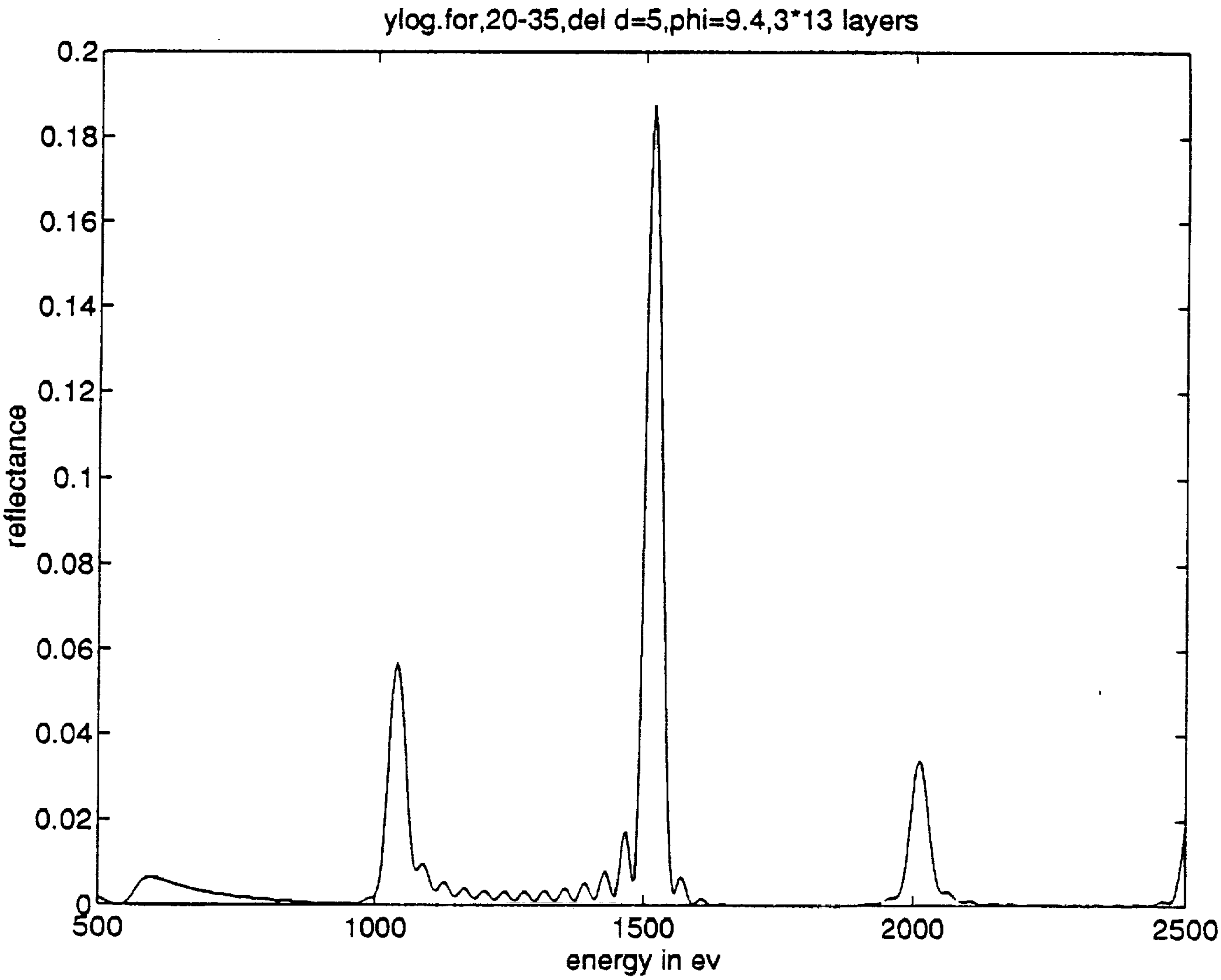


Figure 6(e) t = 1.25

Figure 7: Depth-graded mirror response as a function of increasing change, Δ, in layer-pair thickness.

Figure 7(a) $\Delta = 0.25\ A$

Figure 7(b) $\Delta = 1.0\ A$

Figure 7(c) $\Delta = 2.0\ A$

Figure 7(d) $\Delta = 3.0\ A$

Figure 7(e) $\Delta = 4.0\ A$

Figure 7(f) $\Delta = 5.0\ A$

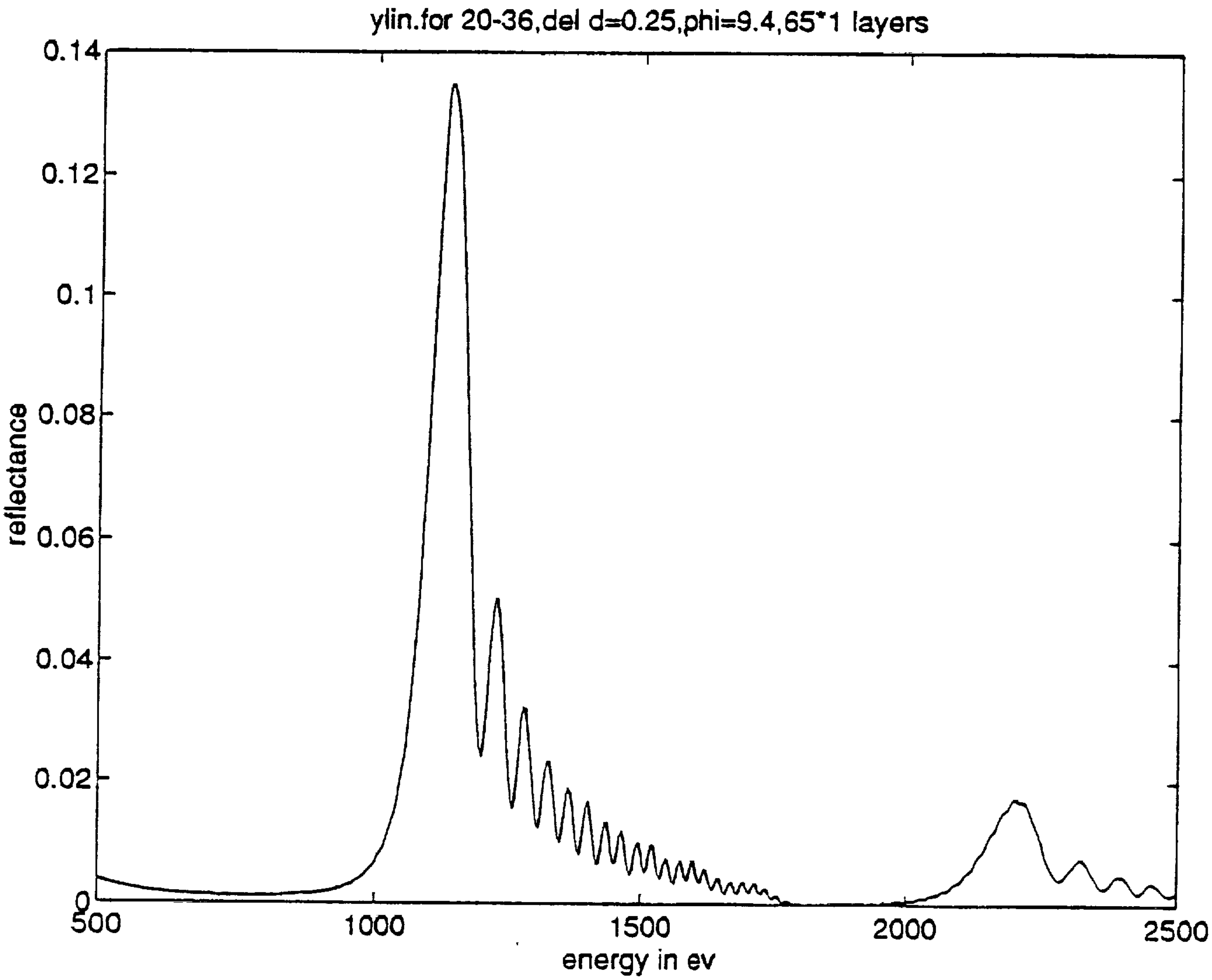


Figure 7(a) $\Delta = 0.25\ A$

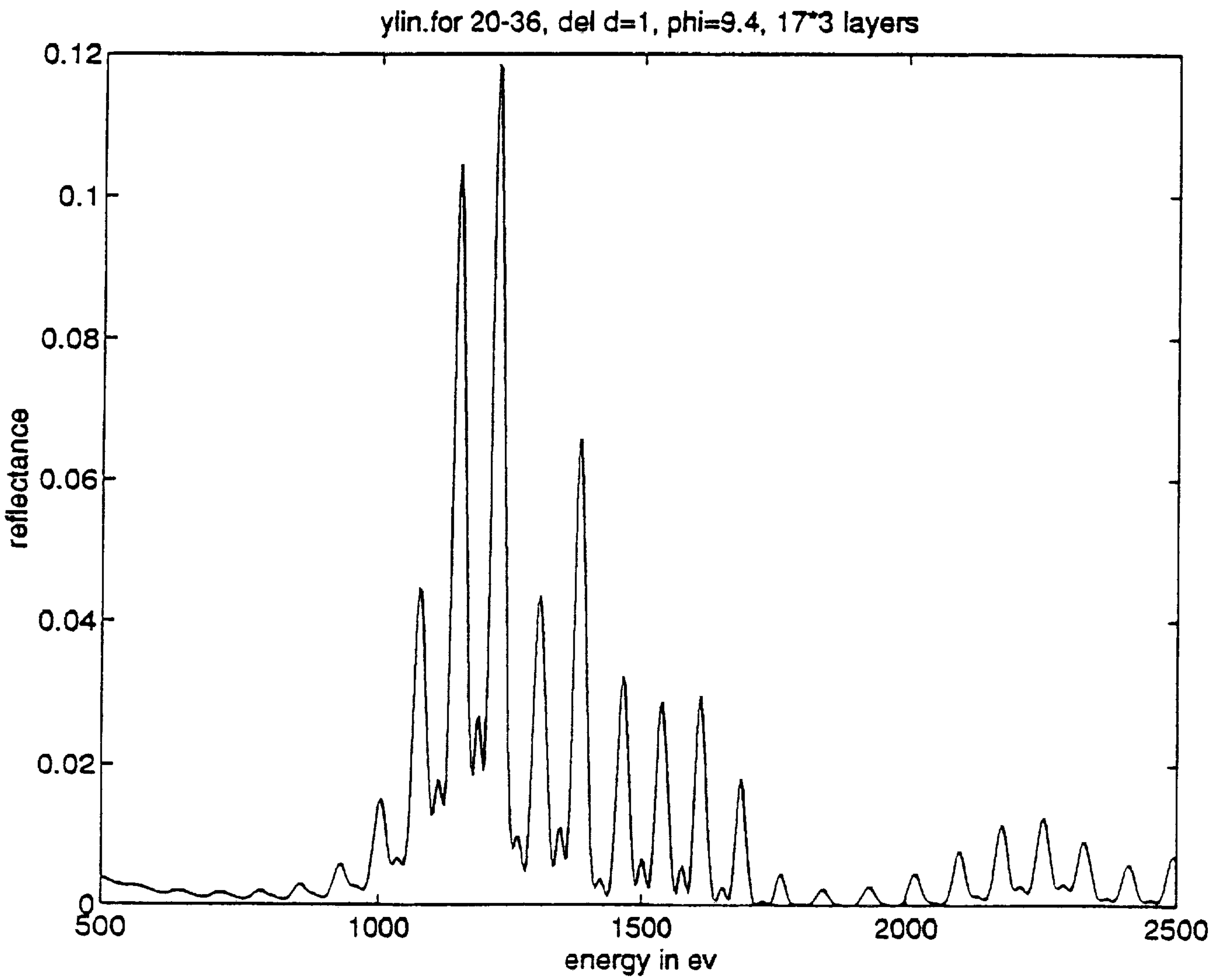


Figure 7(b) $\Delta = 1.0\ A \quad t = 1.1$

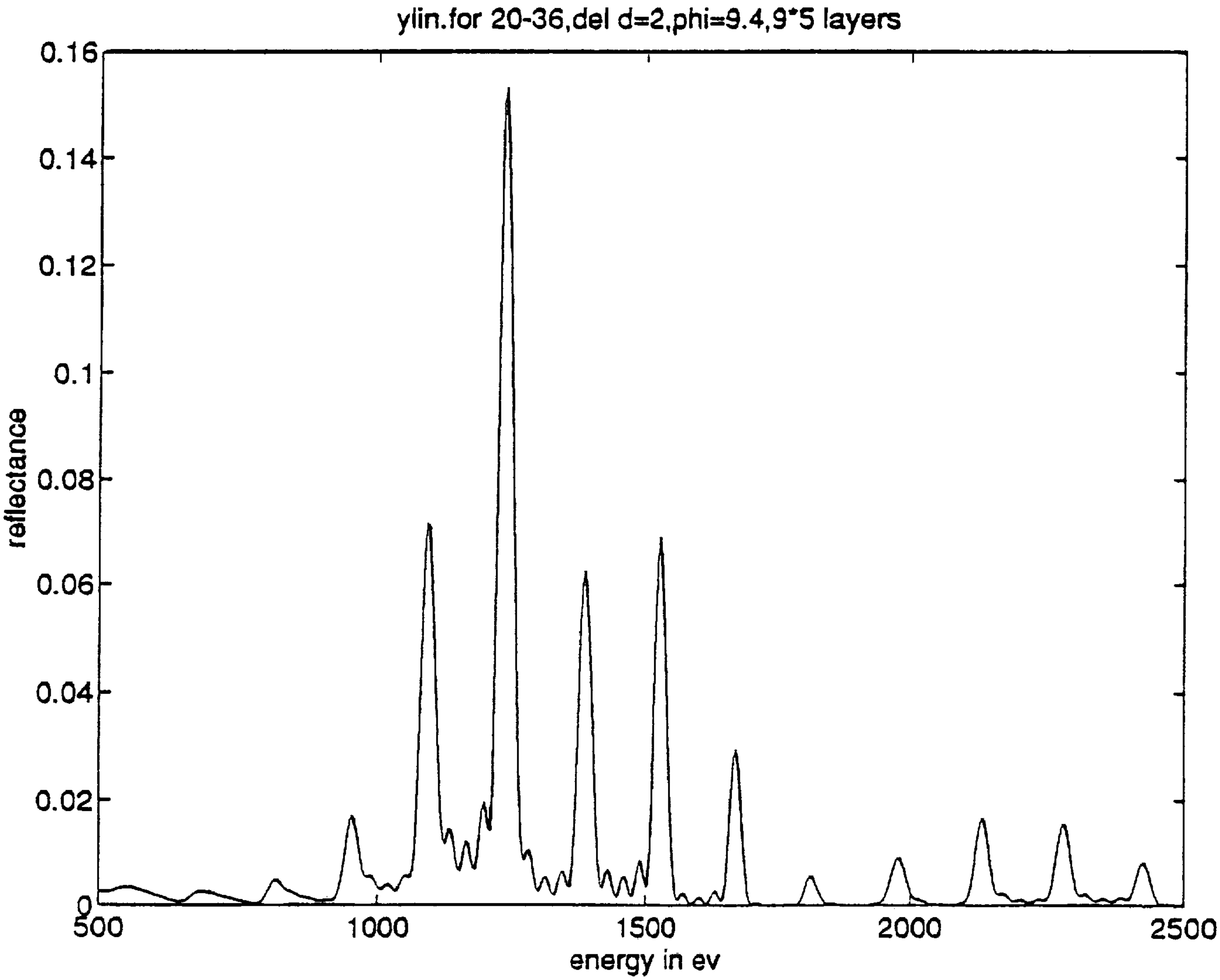


Figure 7(c) $\Delta = 2.0\ A$

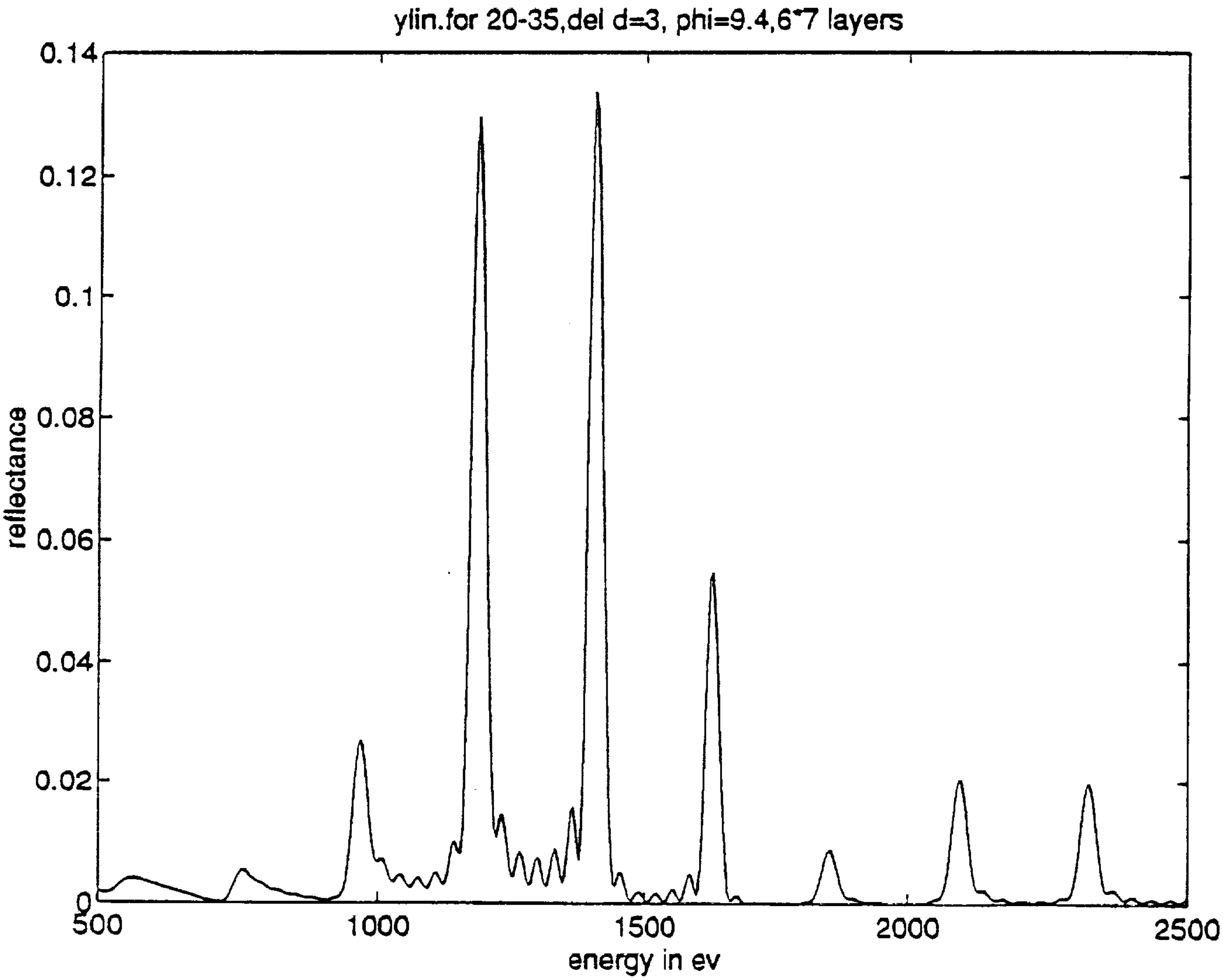


Figure 7(d) $\Delta = 3.0\ A$

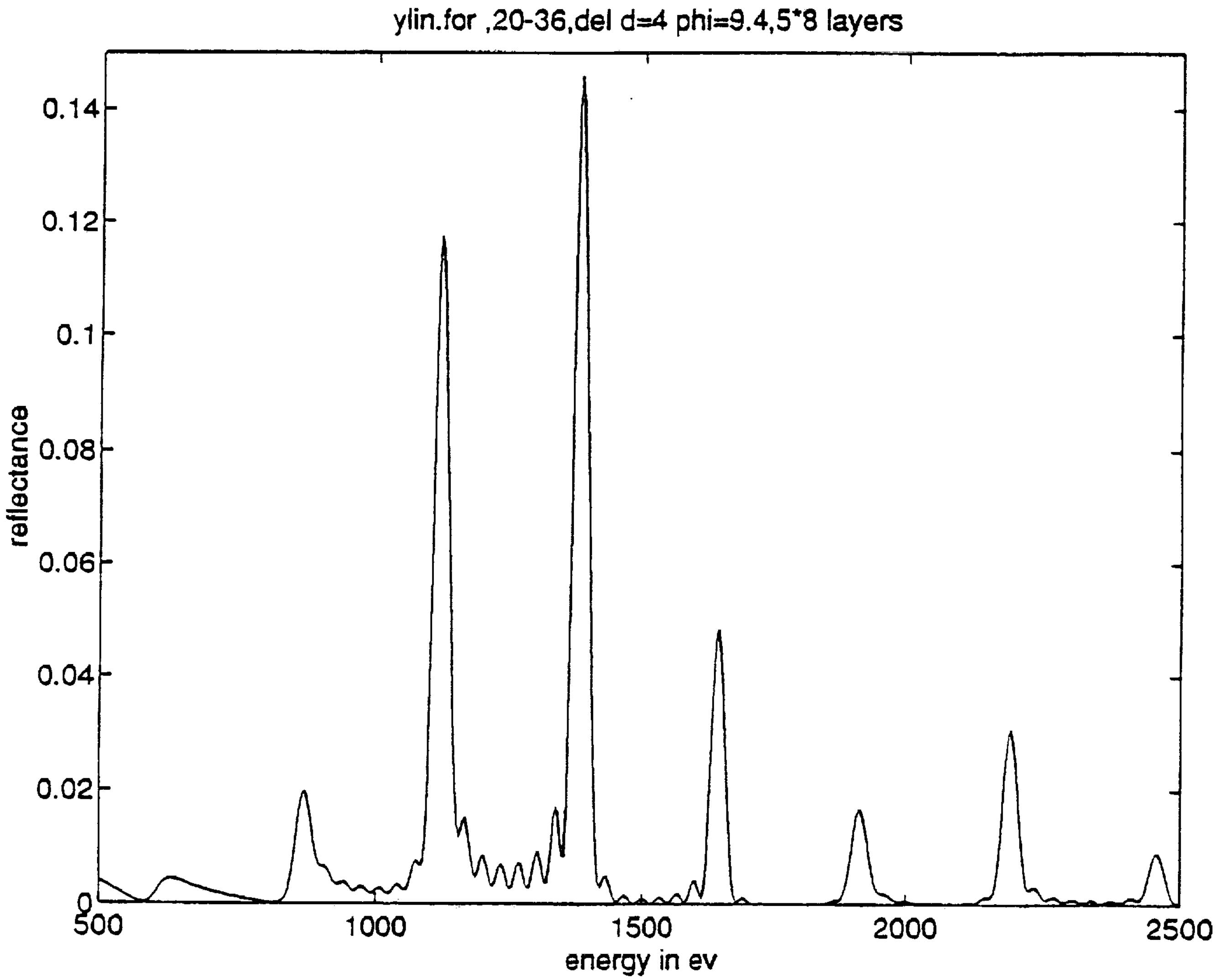


Figure 7(e) $\Delta = 4.0\ A$

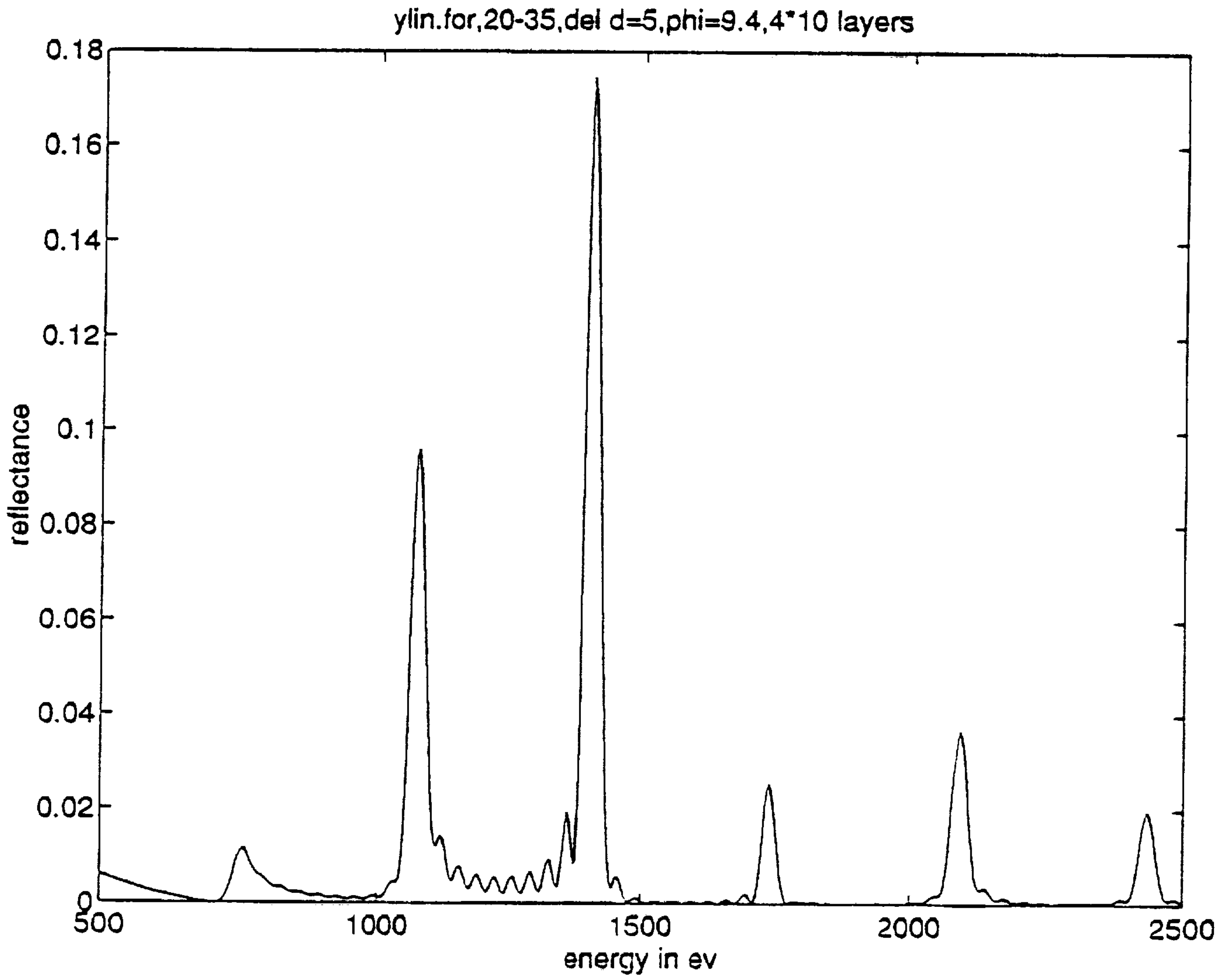


Figure 7(f) $\Delta = 5.0\ A$

Figure 8: Depth-graded mirror response as a function of increasing number of layer-pairs per block (fixed $\Delta = 5\ A$).

Figure 8(a) 2 pairs, block (24-29) A

Figure 8(b) 3 pairs, block (22-32) A

Figure 8(c) 4 pairs, blocks (20-35) A

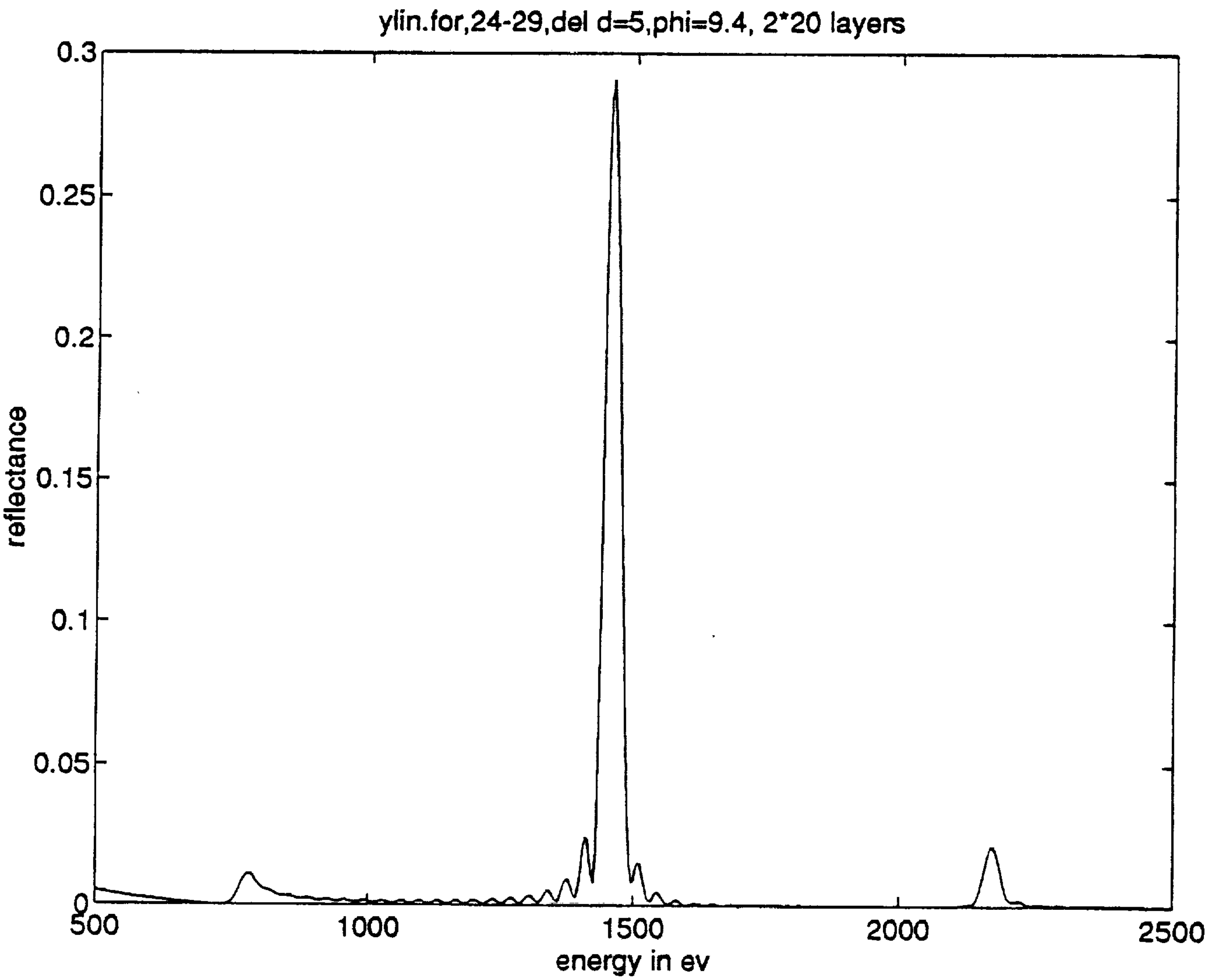


Figure 8(a) 2 pairs, block (24-29) *A*

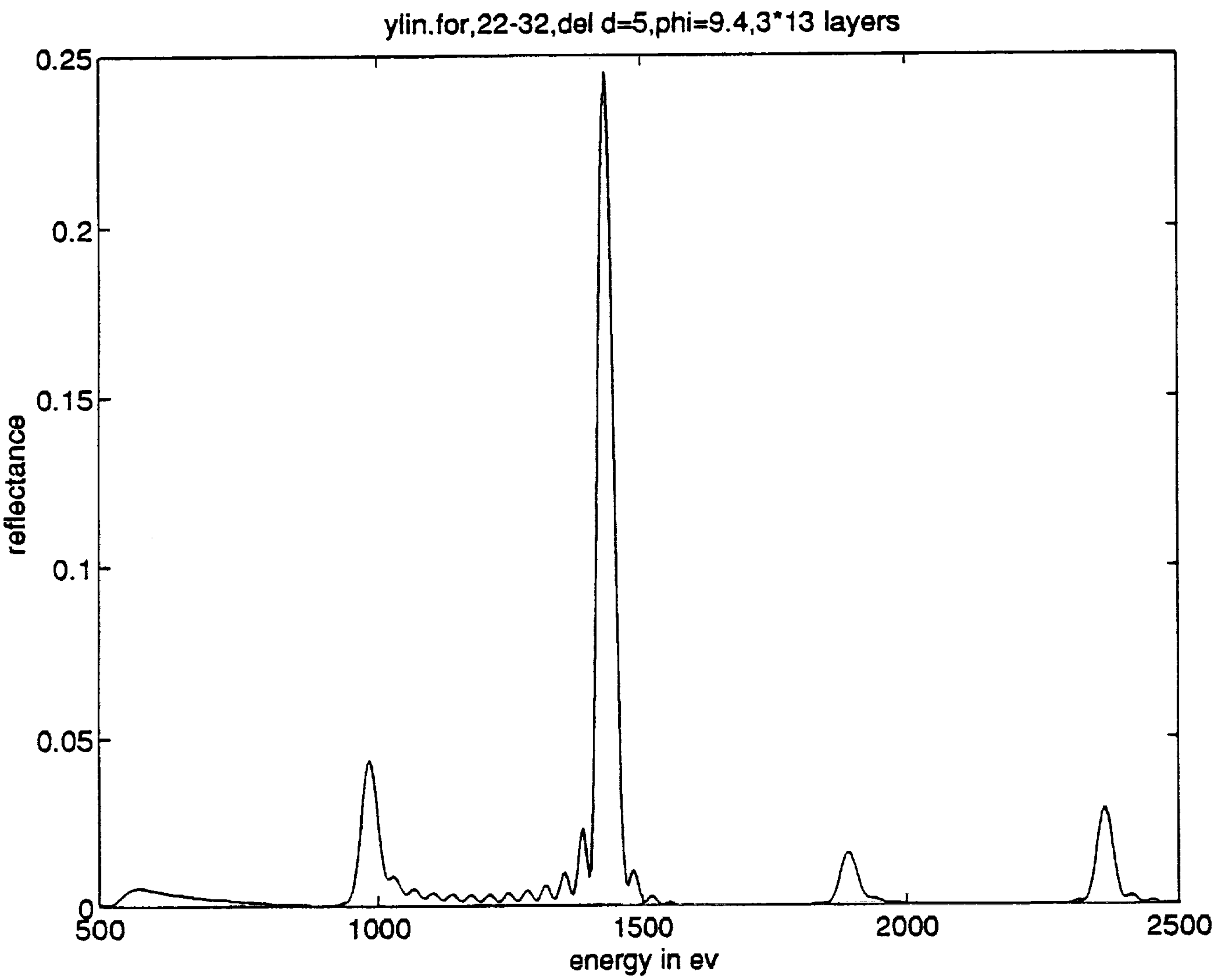


Figure 8(b) 3 pairs, block (22-32) A

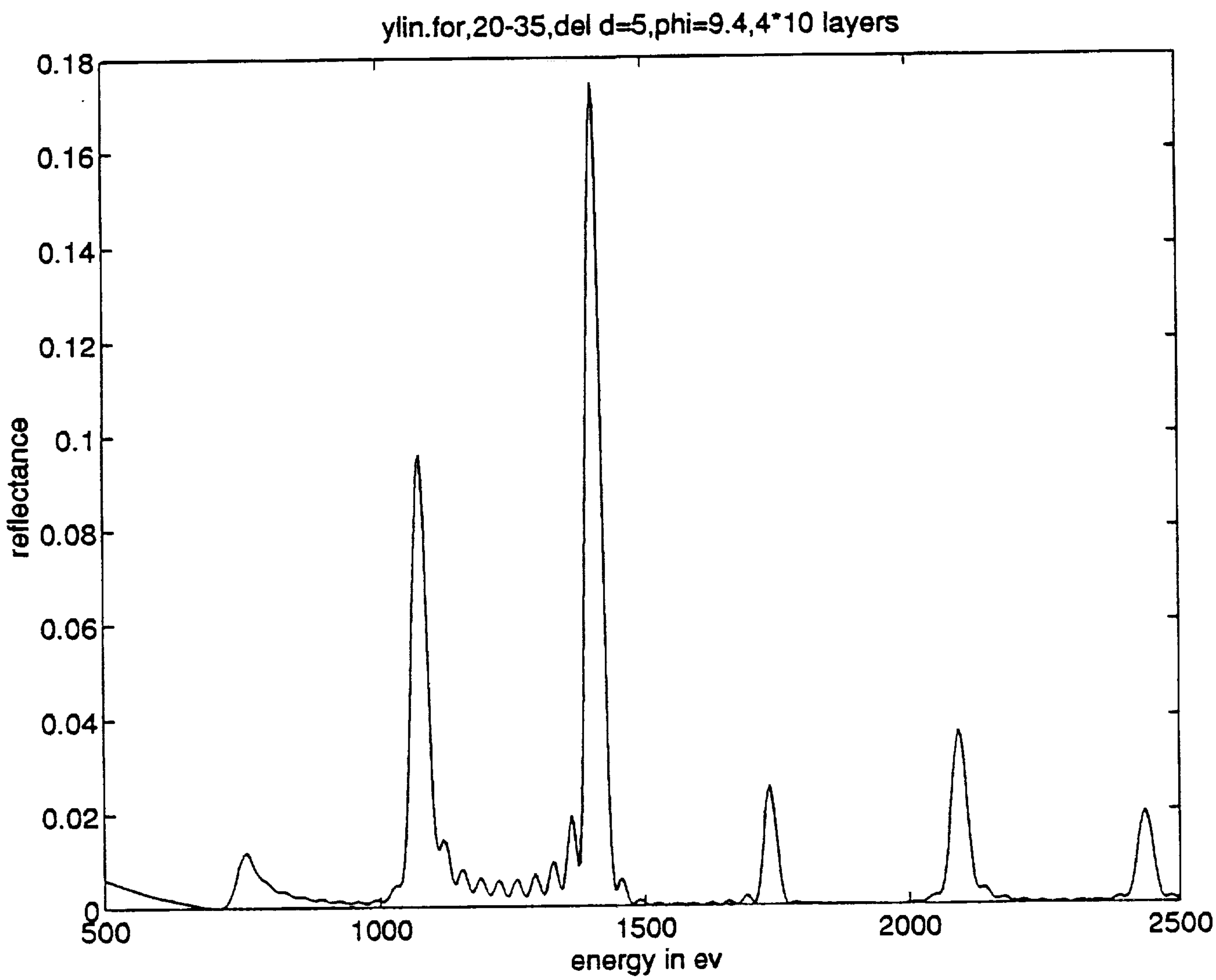


Figure 8(c) 4 pairs, blocks (20-35) A

Figure 9: Depth-graded mirror response as a function of increasing number of layer-pairs per block (fixed $\Delta = 4$ Å).

Figure 9(a) 2 pairs, block (24-32) Å

Figure 9(b) 3 pairs, block (22-34) Å

Figure 9(c) 4 pairs, blocks (20-36) Å

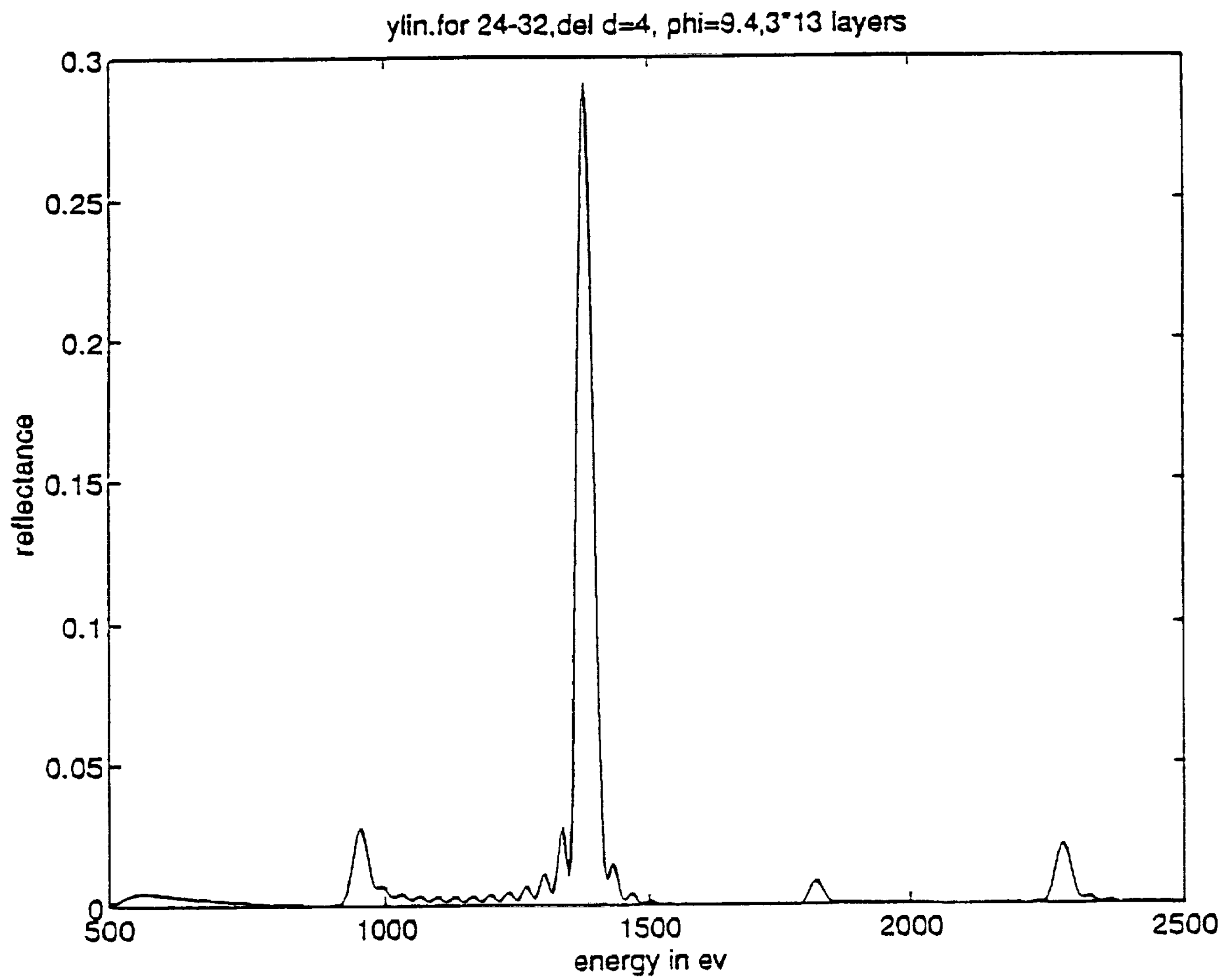


Figure 9(a) 2 pairs, block (24-29) A

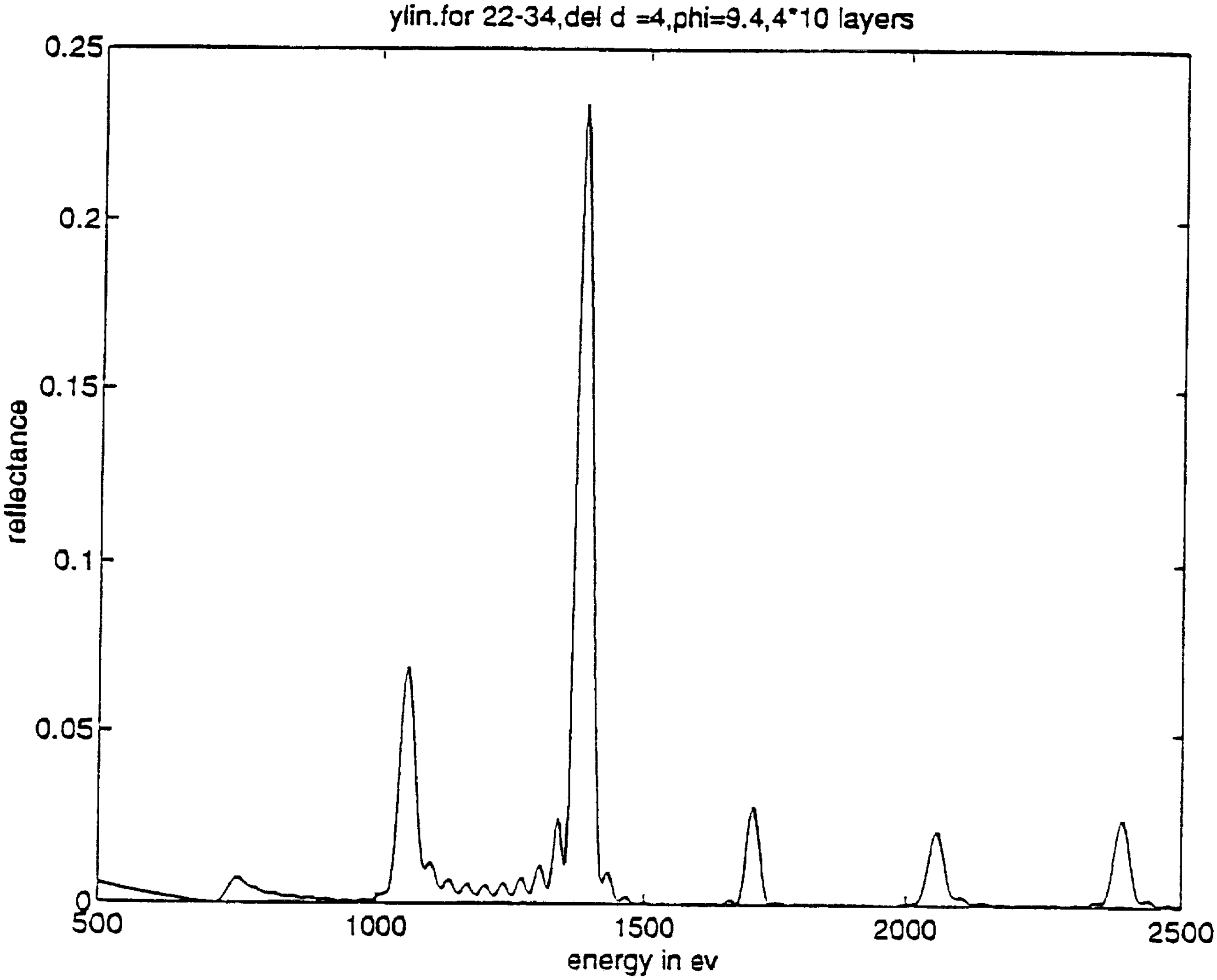


Figure 9(b) 3 pairs, block (22-32) A

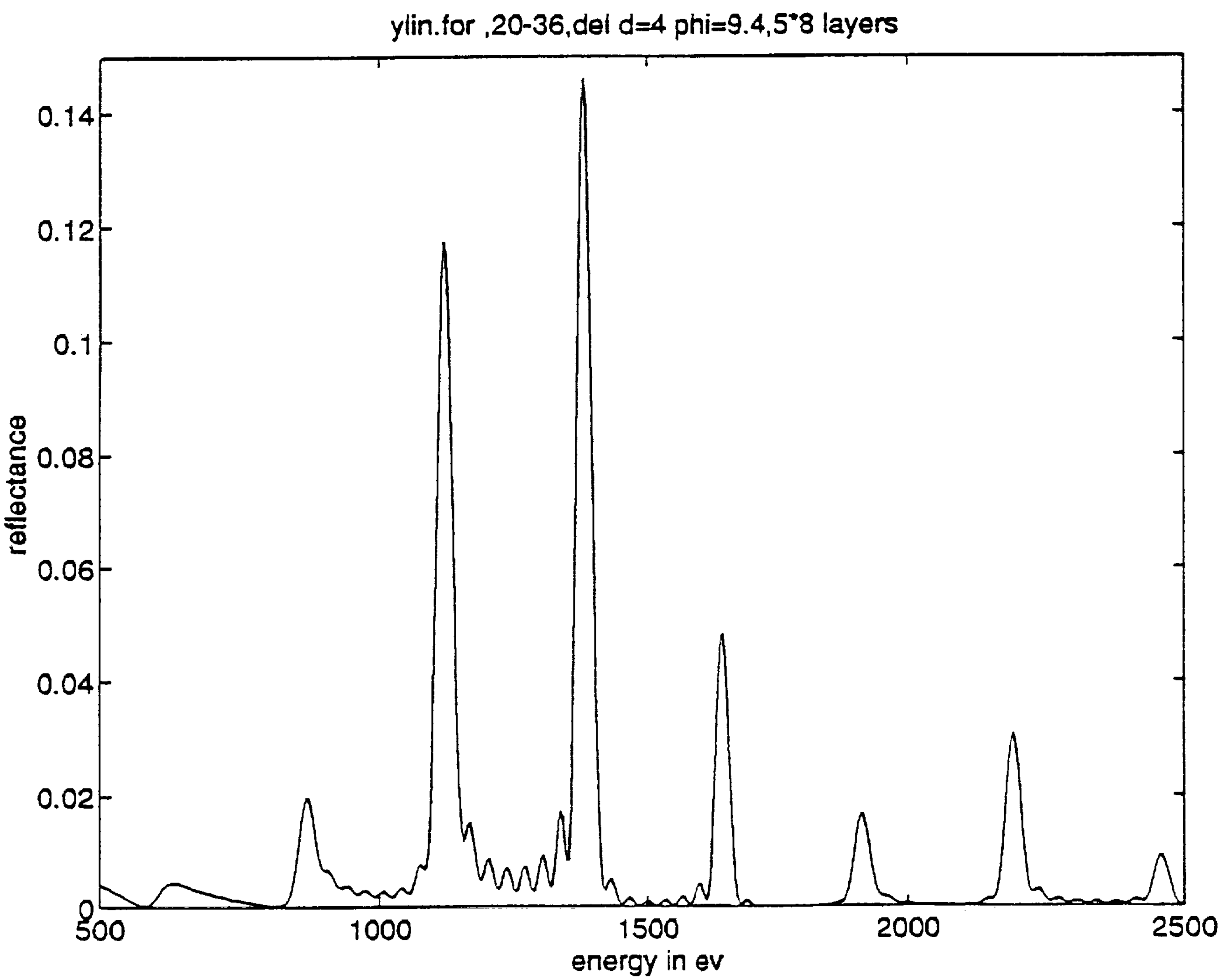


Figure 9(c) 4 pairs, blocks (20-35) A

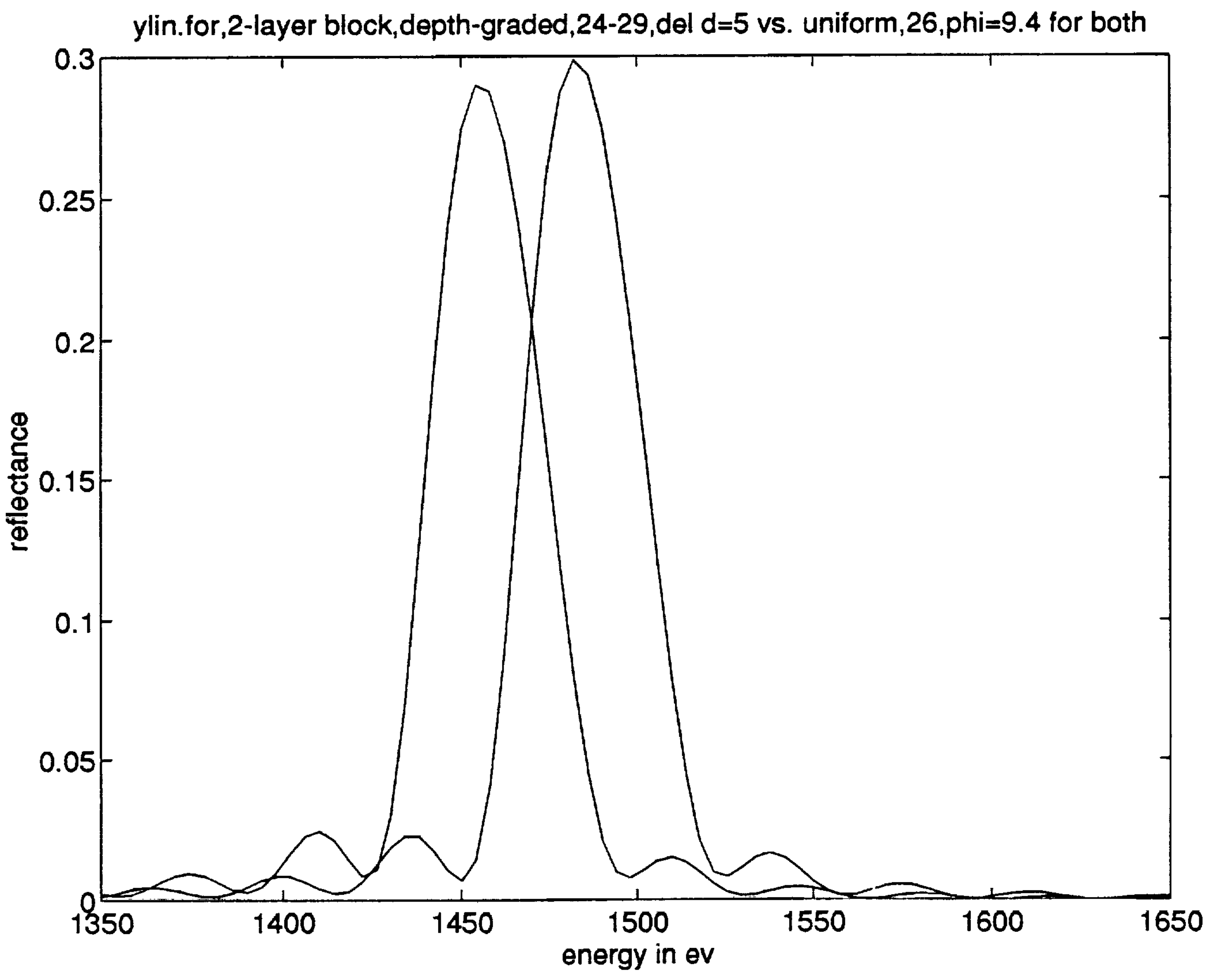


Figure 10: Comparison between a depth-graded, 2-layer per block mirror (on left) and a uniform mirror (on right).

Figure 11: Response from 2-layer per block depth-graded mirrors with fixed $\Delta = 5\ A$ as a function of increasing thickness of the "first" layer.

Figure 11(a) layer thicknesses (20-25) A

Figure 11(b) layer thicknesses (22-27) A

Figure 11(c) layer thicknesses (24-29) A

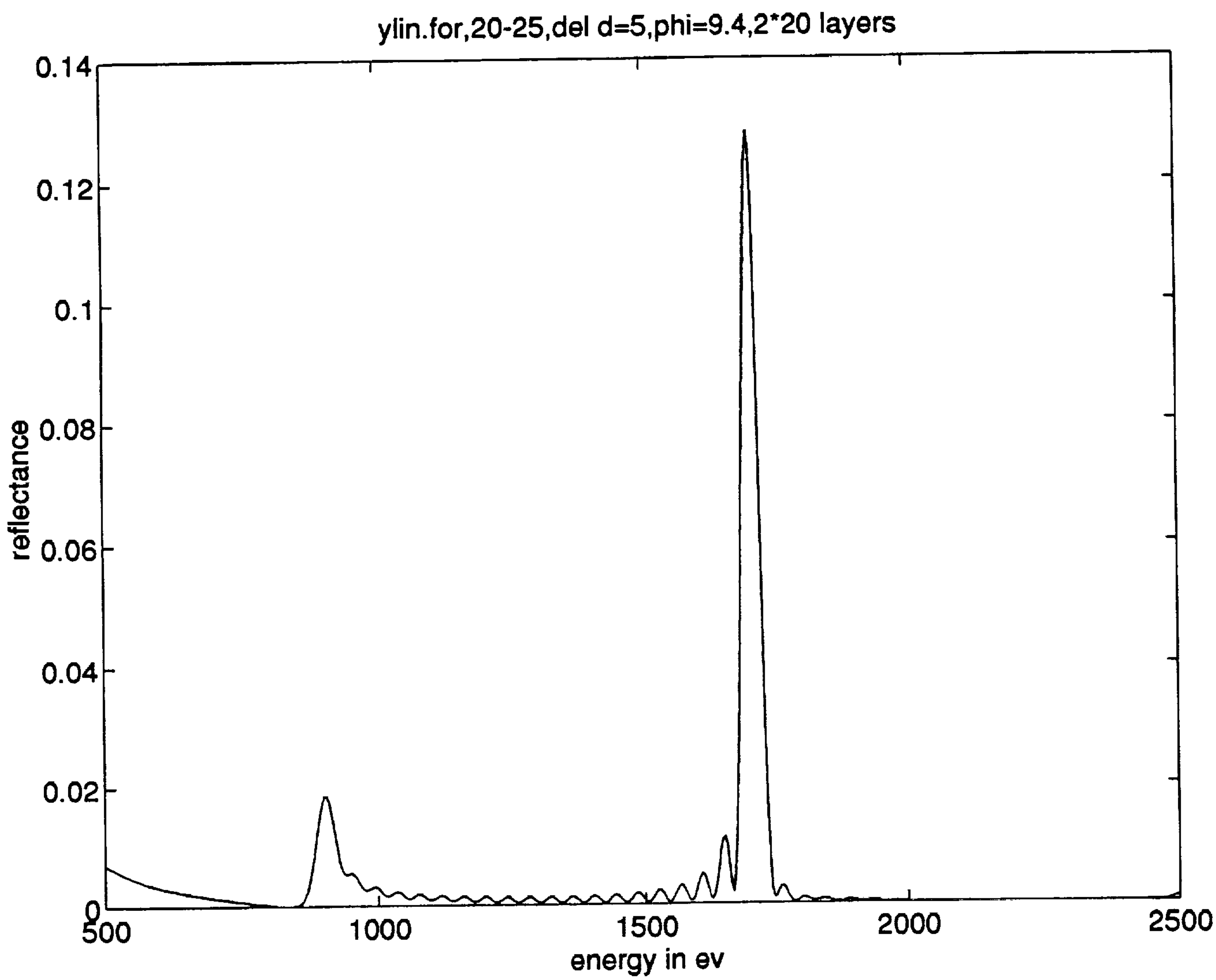


Figure 11(a) layer thicknesses (20-25) Å

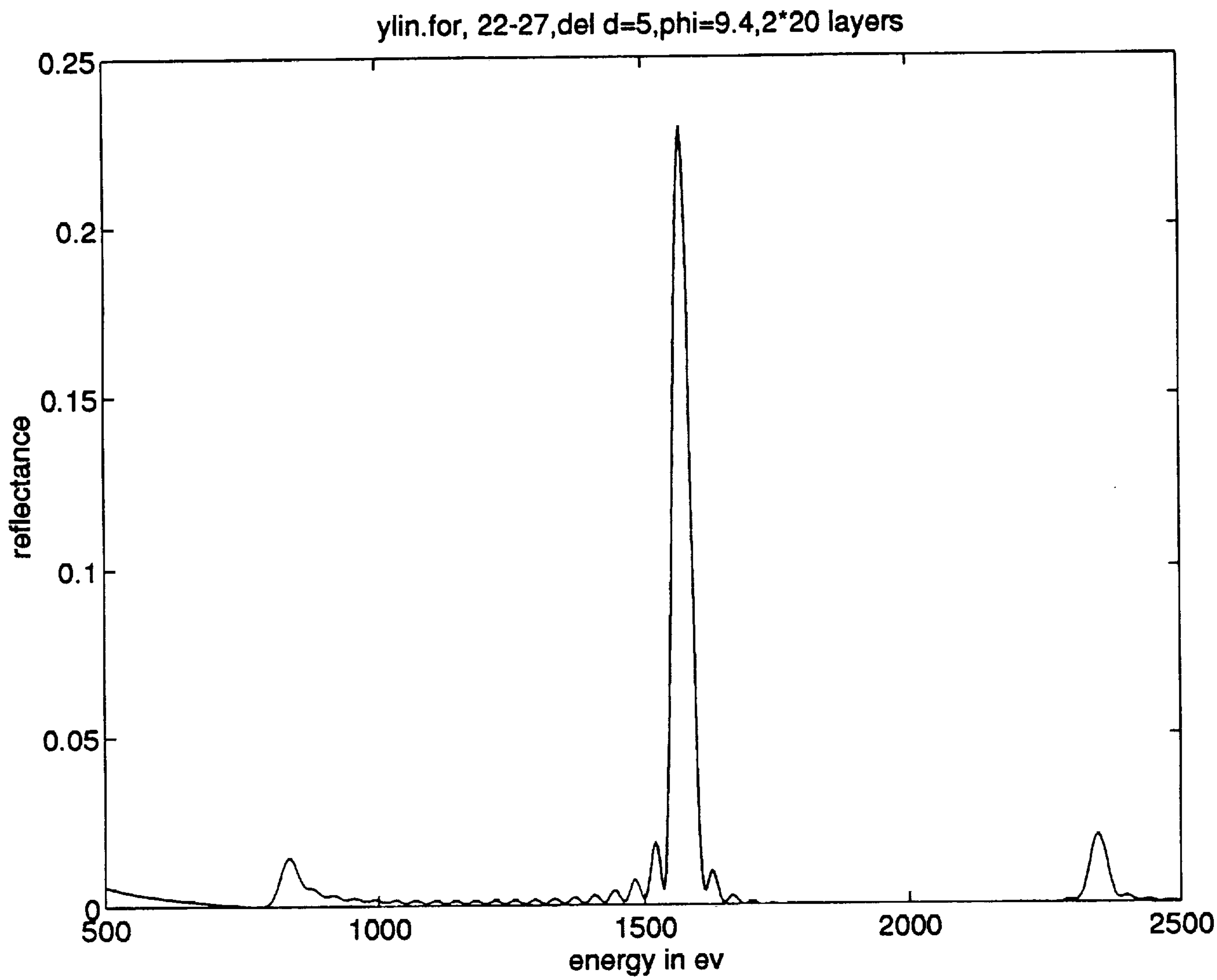


Figure 11(b) layer thicknesses (22-27) A

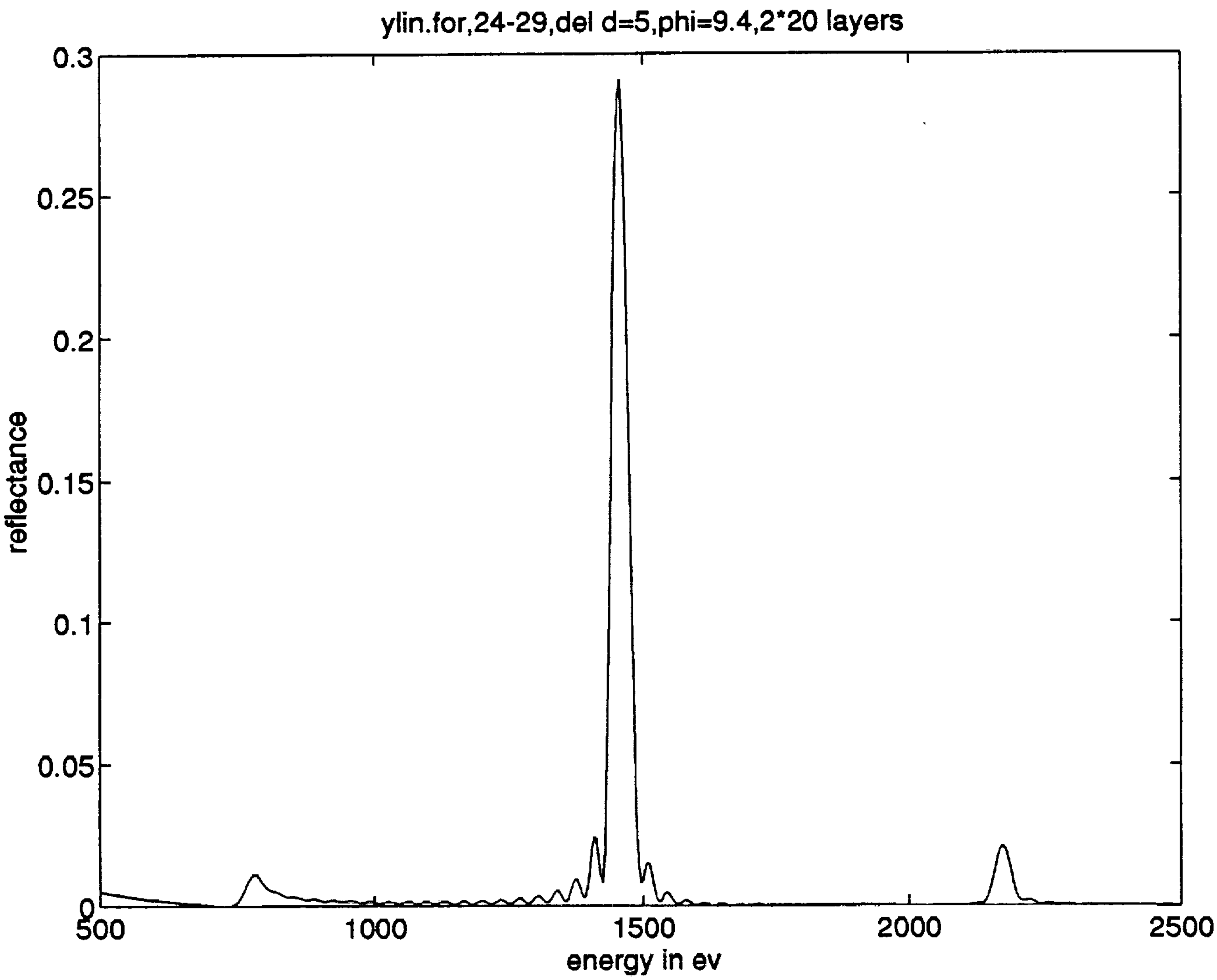


Figure 11(c) layer thicknesses (24-29) A

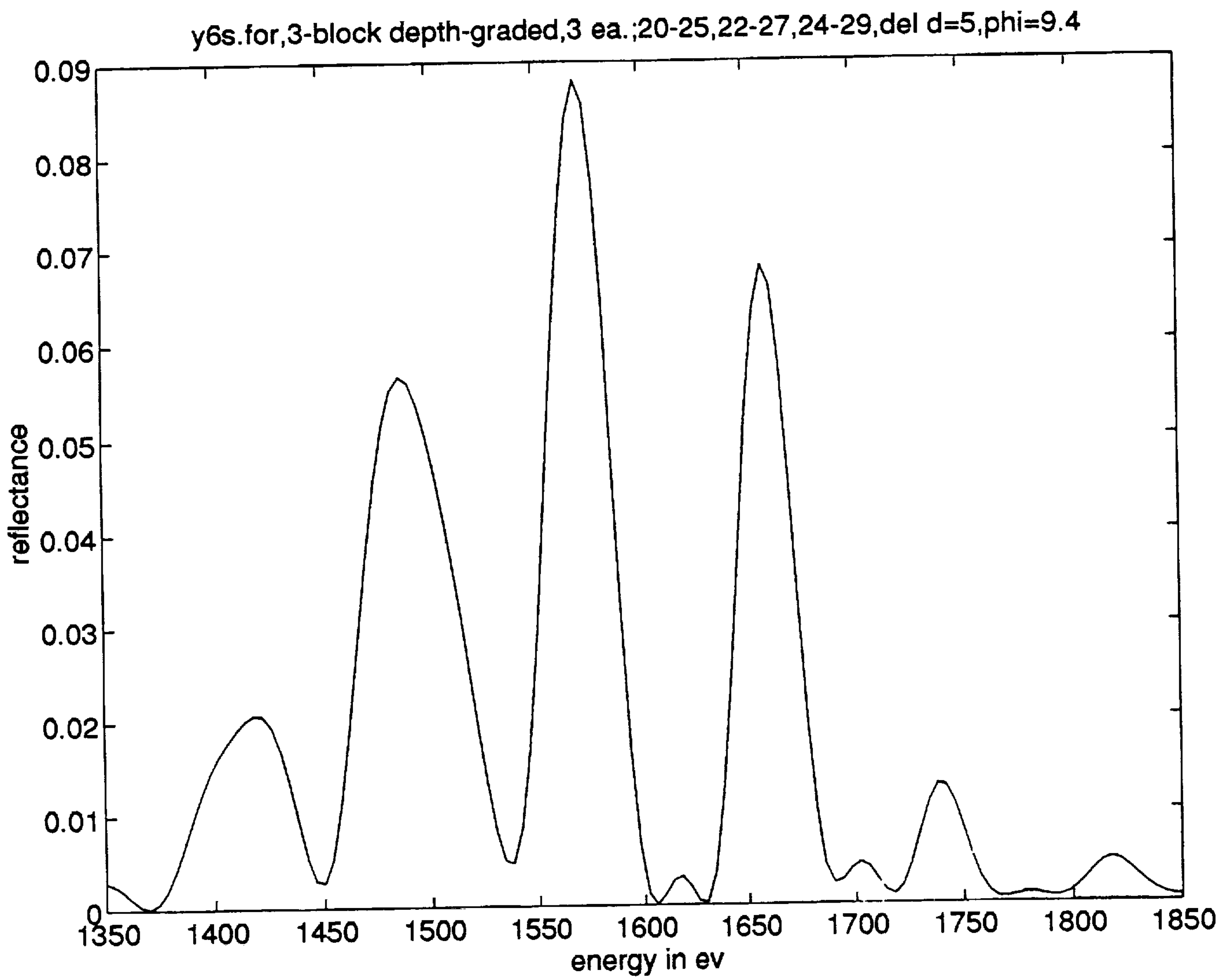


Figure 12: Composite 3-block depth-graded mirror response. Block layers (Å): 20-25, 25-30. (a) 54 total layer pairs.

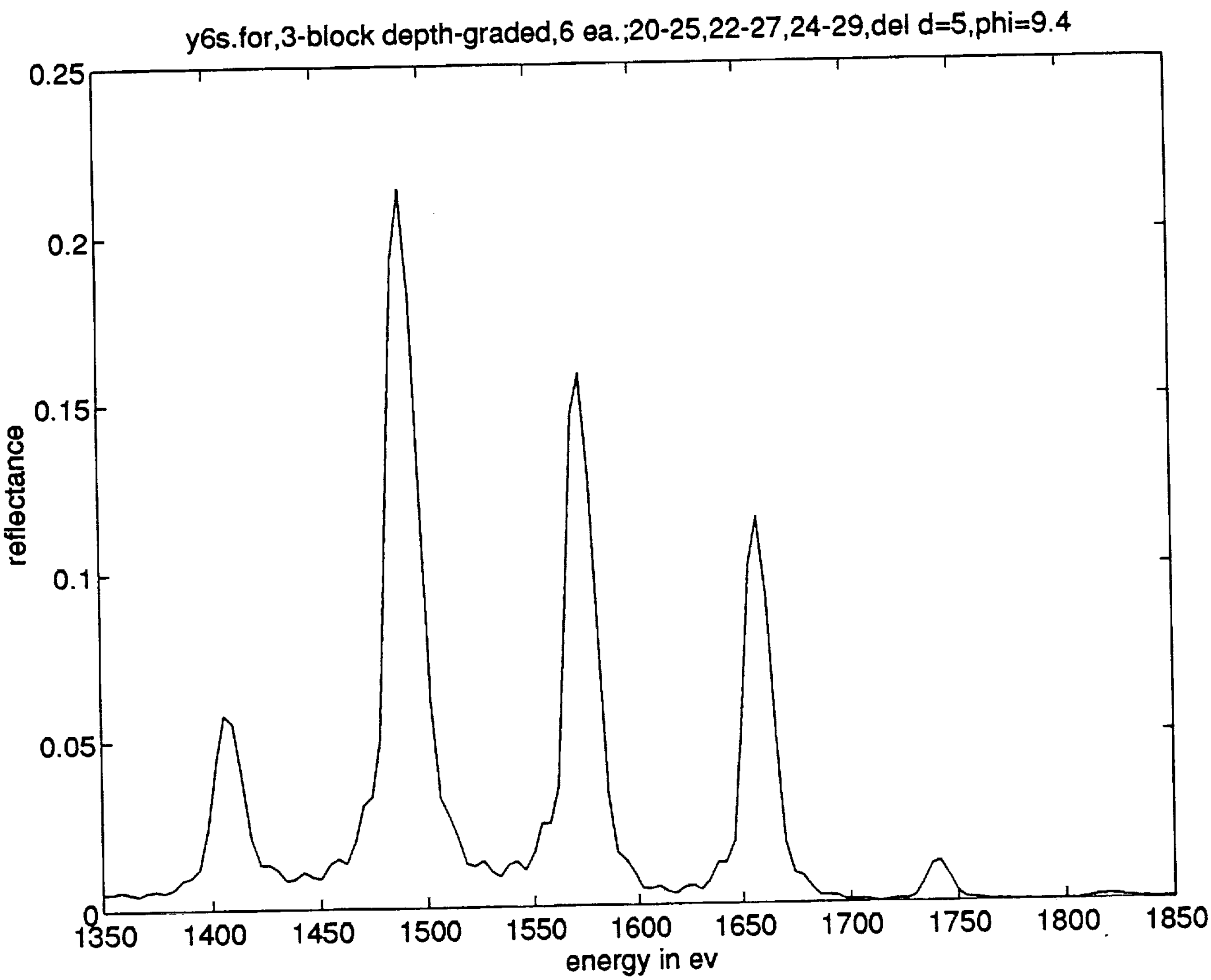


Figure 12: Composite 3-block depth-graded mirror response. Block layers (A): 20-25, 25-30. (b) 108 total layer pairs.

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13. ABSTRACT *(Maximum 200 words)*

The objective of this research was to investigate the possibility of increasing the useful bandwidth of multilayer mirrors. Mirrors "constructed" with non-periodically spaced reflecting surfaces were considered. These structures included depth-graded and laterally-graded mirrors as well as those with reflectors located via a log-periodic spacing rule.

No enhancement of bandwidth resulted from simulations of simple versions of any of the three non-periodic mirrors. However, certain depth-graded structures did exhibit reflectances essentially the same as from uniform mirrors. Moreover, it was found that some control was possible regarding the location (with respect to energy) of the maximum reflectance peak.

Effective bandwidth was increased when composite models were simulated. In two of the cases studied, bandwidth was enhanced by a factor of approximately 3. One model consisted of a depth-graded mirror constructed with three separately defined structures, or blocks. Each block consisted of two layer-pairs repeated three times. Then, the entire 18 layer-pair group was repeated several times. Simulation of this 3 block depth-graded configuration yielded three reflectance peaks, one representative of each depth-graded block.

The other configurations resulting in enhanced bandwidth assumed independently constructed mirrors immediately adjacent to each other and sharing the same substrate. Reflectance peaks from each mirror appeared in the response.

Both basic models show greatly enhanced effective bandwidths even though the reflectance curves appear as non-overlapping for these specific models. Additionally, these configurations are realizable.

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